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A TEMPORAL TUNING MODEL
FOR CHROMATICITY

by

© GREGORY ALAN MACDONALD

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "A Temporal Tuning Model for Chromaticity" submitted by Gregory Alan MacDonald in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

Color has traditionally been considered to have three dimensions: brightness, hue, and saturation. Recent neurological studies (Wiesel and Hubel, 1966) and work on temporal aspects of vision (Nelson and Bartley et al., 1971) suggest, however, that there may be only two. Hue and saturation may be different experiential results of a single color coding process.

In this thesis saturation is investigated in the context of dimensionality. It is studied as a set of temporal phenomena which change in relation to hue and brightness under varying conditions of photic intermittency.

A subjective increase in saturation, termed supersaturation, is produced under certain conditions of intermittency. This phenomenon, along with desaturation, forms the basic evidence for a color processing model based on temporal tuning mechanisms.

In the model, the fundamental notion of tridimensionality is questioned. Saturation is redefined as a time-dependent neurological potential for the production of information for any primary color in relation to, or in isolation from, the other primaries.

A temporal color diagram is introduced as an alternative to existing Euclidean color spaces. It accounts for color mixing, and changes in hue and saturation under both photic intermittency and steady illumination.

Hue and saturation are also studied under intermittency in a deuteranomalous observer. Results support the notion of temporal tuning mechanisms in the visual system and suggest that such anomalies may arise for temporally-based neurological reasons rather than from photochemical deficiencies.

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INTRODUCTION

Color is a conceptually messy subject. In Hellenistic thought it was considered to be a unidimensional matter which occurred isomorphically in both physical and psychological domains. In modern man's ordinary experience it is similarly unidimensional. It is the difference between red, green, blue, orange, and other emic categories. Within science however, explanations for color have become abstracted. They have tended towards increasing complexity, often to the point where the experiential referent is obscured in the formality and rigor of the models which evolved to describe it (see Appendix III).

By the nineteenth century an elaborate conceptual-linguistic structure had developed around the science of color. Within psychology it was firmly thought to have three dimensions: brightness, hue, and saturation. These dimensions corresponded topologically but not isomorphically with their physical derivatives. They formed the superstructure from which current theories differentiated in all relevant disciplines.

For all these attempts to explain color, there has evolved no unified theory which transcends physics, physiology, and psychology. There are however, a number of specialized theories within each of these disciplines

Which have developed from a single generic basis.

The Newtonian color model has traditionally been misused and abused to bridge the epistemological gap between the three disciplines. It has been the prototype for all color spaces and most color mixing models since its inception in 1704. It has been borrowed from and adapted far beyond its range of usefulness and original intention. Today many misconceptions about color can be traced to the polarization of ideas around the Newtonian model.

In particular three classes of problems contribute to this disorganization of ideas. They are:

(1) the conceptual rift between physics and perception,

(2) disagreement on whiteness and dimensionality in color, and

(3) the extent to which color experiences can be considered temporal rather than spatial phenomena.

Some of the problems in these classes derive directly from Newtonian physics. Others have origins in Euclidean space, but they have one thing in common. They are all predicated on assumptions which, accurately or inaccurately, are rooted in man's ordinary experience of the world.

Saturation is salient in each of these three classes of problems. It is perhaps the most poorly understood and least studied of the so-called dimensions of color. Major theories account for it in radically different ways. It is often fitted in and around mechanisms designed principally to explain other dimensions, phenomena, or relationships. Nevertheless, saturation is a pivotal concept in color. It has important implications for both dimensionality and for whiteness. Understanding it may be the key to a much needed restructuring of some of our most basic ideas on color.

Saturation is the focus of this thesis. It is investigated first in a linguistic context, through a conceptual analysis of its involvement in each of the three classes of problems. It is then studied empirically, as a set of temporal phenomena which change in relation to hue and brightness as a function of photic intermittency.

The results of this investigation lead to a redefinition of dimensionality in color. A color space based on temporal tuning mechanisms is presented as an alternative to existing Euclidean color spaces. This color space includes a previously unreported phenomenon called "supersaturation" which occurs under photic intermittency but not ordinarily under continuous illumination.

BASIC CONCEPTUAL PROBLEMS IN COLOR

The first and third classes of problems (the physics-perception rift and space-time) have related origins in Greek thought. They are interpreted here as pre-inferential problems which have become manifest only since the rise of experimental science in the Renaissance. The second class of problems (dimensionality) arises from the interchange of ideas and dependencies within institutionalized structures of experimental science.

THE SEPARATION BETWEEN PHYSICS AND PERCEPTION

The Greeks made no linguistic distinction between color as it was in the real world and the color which they perceived. They were both called chroma. In modern science however, distinctions like wavelength versus hue, or intensity versus brightness are very important. They derive from an artificial dichotomy between physics and percpetion. Topological correspondence between these linguistic categories is postulated, but is far from complete. Brown and black for example, are psychologically "real" colors, but are not included in Newton's color model nor in any other spectral color space. This reflects limitations in both physical color theory and in psychology. Physical models have simply become too specialized to adequately handle psychological data. Nevertheless psychology continues to use them. It has often borrowed indiscriminately and inappropriately from physics. This borrowing did not begin with psychology. It has existed throughout the entire history of science and, in fact, is an integral part of the reason that science ever developed.

Throughout much of the history of ideas in western civilization, physics has been dependent upon psychology, instead of the other way around. Both science and psychology are rooted in man's ordinary experience of events in time and space. Both remained in a pre-inferential or descriptive state until modern times. During the Renaissance, science went through a series of abstractive changes which involved transitions from empirical ways of thinking about the world to theoretical approaches. Traditionally physics had been limited by human sensory capacities, but by the eighteenth century it had become a highly objective, predictive system characterized by organization and disciplined thinking. Psychology and other fledgling sciences were later to emulate this tradition.

The realignment of the relationship between physics and psychology can be summarized by a comparison of man's current notions on perception with those of the Greek atomists.

Hellenistic man thought he saw the world exactly as it was. Epicurus (ca. 300 B.C.) postulated that perception occurred because objects gave off faint images of themselves called eidola which travelled through the air and up the optic nerve to make direct contact with the brain. This idea, that perception is veridical, lasted until the nineteenth century.

Today there is a different conventional wisdom surrounding perception. We still believe there is a real world, but we now think that our perceptual systems give us only part or a representation of this world. Furthermore, we consider our particular representation to be not the only one possible. Illustrations of this philosophy are found in biological limitations of our senses. For example, neurological restrictions in our visual system allow us to see only a very small part of the electromagnetic spectrum ($\simeq$380 - 720 nm). We have somesthetic senses which extend the range of this perception slightly into the infrared and ultraviolet, but beyond the capacities of these skin senses, we can only measure the spectrum with physical instruments.

Several developments led to the separation of physics from perception. Some of these involved growing dependencies upon abstractive or theoretical language systems like mathematics, but others involved changes in experimental methodology. Two in particular bear directly upon color.

One of these occurred rather abruptly in the seventeenth century with the invention of the calculus. It involved a transition in ways of thinking about cause-effect relationships. Specifically, it involved a change from empirical methods of hypothesis testing to theoretical experimentation. Newton was instrumental in effecting this change. Before calculus, experimental physics had a direct empirical referent. Galileo, Kepler, Lippershey, Janssen, Leonardo, Torricelli, Newton himself and many others made important contributions to science through ideas which were derived and tested visually. These contributions were delivered in abstractive terms, but they came originally from ordinary perceptual experiences of chandeliers swinging or colors coming from prisms, etc. As Michotte (1946) and others have pointed out, there is something very basic in the cause-effect relationship which results from the association of perceptually contiguous events. It is interesting to conjecture what Newton's contribution to science might have been if he were blind, or even color blind.

Within calculus, hypotheses could be derived and tested independently of any direct experiential referent.

Much of the modern work on the physics of light is done in this way. Examples are found in the measurement of the speed of light (Michelson and Morley, 1873), in Quantum theory (Planck, 1900), and in Relativity (Einstein, 1905). Calculus provided a conceptual-linguistic superstructure which helped mediate the transformation of physics from a perceptually-based descriptive study of the world to a theoretical-predictive study.

The second development was abstractive as well, but consisted of a transition in hardware rather than in software. It began with extensions of the human senses in experimentation and later involved the actual replacement of the human observer by machines. It began prior to the Industrial Revolution and continues today.

With increasing sophistication in scientific procedure in the sixteenth and seventeenth centuries, methodological attention became focused on precision. In time, science required a level of accuracy which, in many cases, was beyond the capacity of the normal human observer. Man was becoming the weak link in a sophisticated predictive system.

The first stage of adjustment to these requirements of science consisted of technological aids to extend or improve man's senses. Examples are spectacles, telescopes, microscopes, clocks, and more recently, telephones, telegraphs, and television.[1]

The second stage of adjustment started with the Industrial Revolution. It consisted of an actual replacement of human sensory functions with machines. Thermostats, feature analyzers, punch card readers, photo electric cells, radiometry, spectrometry and gas chromatography all developed in this tradition.

By the mid-nineteenth century light and color could be discriminated more accurately by machines than by the human eye. The direct empirical referent had been effectively removed from color science.

As physics became separated from perception, psychophysics arose at the interface and has acted as a liasion system between the two. It has helped to establish a guise of scientific respectability for psychology by facilitating the transfer of ideas from physics. Many good ideas came to psychology this way but along with them came some assumptions which were fundamentally bad. Tridimensionality in color is one of them.

TRIDIMENSIONALITY

The tridimensionality of color in psychology comes directly from Newtonian physics. It may be one of the biggest conceptual problems in the history of ideas on color. Nevertheless, it is deeply ingrained in our thinking. It is reflected in theories (Helmholtz, 1856; Bartley, 1938, 1958), process models (Hurvich and Jameson, 1955) and in color spaces (Munsell, 1942; Ostwald, 1948).

The veridicality of tridimensionality has important implications for the dimensional status of saturation, but tridimensionality is misleading for two reasons:

Firstly, the idea that color has independent dimensions of any number is questionable, and secondly, that the number should be three is even more doubtful.

In a three-dimensional color space, a red-orange distinction is categorically different from a red-pink distinction. The former is a hue change whereas the latter is a saturation difference. In more primitive conceptualizations however, pink and orange may be just emic categories which bear the same relationship to be primary color, red. Anthropological evidence (Berlin and Kay, 1969) suggests that the most undifferentiated color spaces have just two categories, black and white. The next inclusion is usually red, then green, yellow, and blue appear.[2] Orange, pink, violet, and others are found usually only in highly differentiated language systems, and dimensionality represents a multi-tiered system of classification which is peculiar to scientific types of conceptualization. Heider (1972) argues that color naming has an underlying biological basis, since these basic language categories or focal color areas are similar in linguistically unrelated cultures.

In general, the concept of dimensionality implies orthogonality. Physical color theory may have independent dimensions of wavelength and intensity but the corresponding psychological dimensions of hue and brightness are not independent. They are empirically separable to a certain extent but both psychological and neurological evidence now suggest interactive rather than discrete coding systems for these experiences.

Experiential evidence for interaction between luminosity and chromaticity systems is found in phenomena like the Purkinje shift (in Hecht, 1921) and the Bezold-Brücke hue changes (in Wildt and Bouman, 1968). Another type of evidence for interactive systems is found in brightness, hue, and saturation changes which occur under photic intermittency. This will be introduced later.

Neurological evidence likewise does not support tridimensionality. Von Kries (1897) first suggested separate photopic and scotopic systems but considered them in a Darwinian or functional context rather than in terms of differences between brightness and color. Neurological and spectrophotometric studies by Rushton (1962), Polyak (1957), MacNichol (1964), etc. have since documented the Duplicity Theory. Others (DeValois, 1965;

Weisel and Hubel, 1966) have delineated an anatomical basis for both chromaticity and luminosity systems at the thalamic level, but as yet, no separate anatomical structures for saturation have been found.

Current neurological evidence suggests that saturation may be a bi-product of the interaction between luminosity and chromaticity processes. In the retinal architecture for example, there are separate rod and cone receptor systems, however, these interact laterally via mediating amacrine and horizontal cells (Polyak, 1957; DeValois, 1965).

At the cortical level, electrophysiological evidence differentiates luminosity and chromaticity, but again there is no special evidence for saturation. Ellingson (1956) and Harter, Eason, and White (1964) report shape variations in cortical envelopes for different wavelengths. Dustman and Beck (1963) and Shipley, Jones, and Fry (1968) report that the waveshapes of visual evoked potentials are wavelength specific, and that the latency and amplitude of cortical response is related to the luminosity of the photic input.

In the lateral geniculate nucleus (LGN) luminosity and chromaticity processes are spatially separate for the most part, but interactions do occur. Luminosity seems to be coded in the two ventral layers by certain types of cells, and chromaticity in the four dorsal layers by other types of cells (DeValois, 1965; Weisel and Hubel, 1966). The separation of these types of cells in the two segments is not complete, however. A certain percentage of overlapping occurs which may provide a ratio or interactive mechanism for saturation.

Two questions arise from the confusion of ideas on interactive systems:

(1) if saturation is a bi-product, then to what extent is it related to each of hue and brightness, and

(2) how are saturation and whiteness related.

Approaches to these questions have centered around the traditions of nativism and empiricism. The Young-Helmholtz Trichromatic Theory and Hering's Theory of Opponent Processes account for whiteness in totally different ways. Their differences are critical and bear directly upon both saturation and dimensionality.

THE NEWTONIAN BASIS CF TRICHROMATIC THEORY

The Trichromatic theory is a direct development of the Newtonian color mixing model. It is an archetypic example of the extent to which Newton's influence has extended to fields which his theories were not intended to explain. Like Euclid and Aristotle, Newton gained such a measure of respect that to a certain extent he became thought of as a demigod. People began to think he was infallible, which greatly enhanced his influence in the scientific world.

In 1675 he denoted seven spectral colors and postulated mathematical types of relationships between them on the basis of musical theory. Each color had an analogous note in the octave scale. This analogy was crude, but it formed the prototype for most later mathematical models of color mixing. In 1704 Newton derived a color circle from the spectral colors which has served as the basis for all subsequent color diagrams including circles, squares, triangles, modified triangles (such as those of König and Dieterici, 1892; and the 1931 CIE model), and three dimensional models like those of Munsell (1942), Ostwald (1948), Nickerson and Newhall (1945), and Munn (1951).

Newton was convinced that purple completed the spectral gap between red and violet. His color space omitted variation in brightness. It provided only for differences in hue and saturation. When two hues of any location within the circle were mixed, the resultant was an intermediate hue of decreased saturation. The degree of reduction in saturation was inversely related to the linear or chord distance between the original hues. The further apart they were in the circle, the paler the resultant of their mixture. Whiteness and all greys between white and black were considered the result of compounds of hues rather than separate hues in and of themselves. In a sense though, they were different from the spectral hues, for to change a grey to white, Newton thought that one had only to increase the amount of light.

Several strong assumptions about saturation and dimensionality permeate this model.

The first is that hue and saturation are different from brightness since they are related through color mixing in a way which does not include brightness. The second is that whiteness, being a mixture of the spectral hues, is essentially different from the other colors; and thirdly, whiteness and saturation are related and may in fact be just magnitude differences of a single system since they both result from similar hue mixing processes.

Tridimensionality is implicit in this model, however, the degree of dimensional orthogonality is not clear. On the one hand, Newton does not include brightness in his model, but he does relate brightness to whiteness through the reduction of greys to white (which involves increasing the amount of light). Hue and saturation, although theoretically separate in his color diagram, are also related through color mixing.

These assumptions are an integral part of the Young-Helmholtz theory.

TRICHROMATIC THEORY

The Trichromatic Theory of color is deeply rooted in physics and in the empirical philosophy of science. In 1802 the English physicist, Thomas Young, anticipated Müller's (1826) Doctrine of Specific Nerve Energies for the visual system. He suggested that the retina probably contains three different kinds of light sensitive substances, each maximally sensitive to a different part of the spectrum. Excitation from each of these substances is transmitted along separate pathways to the brain where the information is combined to reproduce the colors of the real world.

In 1856 Helmholtz revised this model and introduced color-mixing processes from Newton's theory. Like Newton, he considered color to have three dimensions: brightness, hue, and saturation. He developed an elaborate mathematical model of color mixing and postulated the three primary colors to be red, yellow, and blue. Recent spectrophotometric studies (MacNichol, 1964) support his model and show the absorption peaks of the three retinal photopic pigments to be 447nm (blue-violet), 540nm (green), and 577nm (yellow).

The Young-Helmholtz model has a clear, concise explanation for color. Hue and saturation are related through color mixture. Brightness is independent of these two dimensions. Each discriminable color results from the proper ratio of excitation of the three types of nerve fibers. As in Newton's theory, whiteness is different from the three primary hues, for it has no unique physiological process. It arises as a result of color mixing when all three systems are excited equally. Pale or desaturated hues arise as the result of the same mixing process, but only when the three systems are excited in different proportions. Saturation and whiteness in the trichromatic theory are not different concepts or processes. They are just gradational results of a single color mixing process. In Helmholtz's theory, as in Newton's, black and brown are not well accounted for.

Hering's theory offers a different account of saturation and whiteness.

THE THEORY OF OPPONENT PROCESSES

The theory of opponent processes is grounded in nativism and phenomenology. Hering considered many of the world's physical processes to be dichotomous and bidirectional in nature. For him, temperature was not defined in terms of the movement of molecules where cold is just the absence of heat. He proposed a chemical analogy for temperature where hot and cold are separate entities derived from discrete and opposing processes of anabolism and catabolism.

This chemical analogy carried over to Hering's notions of color. He thought that color could be accounted for by three bi-directional systems α, β, and γ. Each of these produces one primary color through the process of assimilation and another throughout the process of dissimilation. The primary color pairs were red-green, blue-yellow, and black-white.

The important feature of his theory for the present study is that whiteness was considered to be a "real" primary color with an independent coding process rather than the result of a mixture of other primaries. In Hering's system color mixing occurred centrally rather than peripherally. The degree of saturation depends upon the extent to which the white-black system interacts with the other two systems. Whiteness and saturation result from different processes, rather than from gradational differences of a single color mixing process.

Hering's theory was supported in the beginning by experimental evidence of visual phenomena like color blindness and afterimages where colors seem to operate in complementary pairs. Since the development of psychophysical methodology, the theory has been further developed and elaborated by Hurvich and Jameson. Lately it has received neurological support through the single-unit recording work of DeValois, and Hubel and Weisel.

Thus, there are two major theories of color which differ on explanations for saturation and whiteness. Both are atomistic rather than molar, and both are state models rather than process models. Helmholtz's theory is peripherally based whereas Hering's is more centrally based, but neither successfully accounts for color *in toto*.

Physiological work[1] now supports the idea that we cannot understand visual processing in terms of static events which occur at specific locations in the nervous system. Vision can only be understood in terms of activity in the total pathway. Time rather than space as a basis for neural processing can facilitate this molar approach to the study of vision.

COLOR AS A TEMPORAL PHENOMENON

Until recently, man has considered his visual experience of the world to be spatially coded in the nervous system. Early accounts of vision in optics and psychology dealt with matters like acuity and the localization of surfaces in space. Explanations for size, shape, distance, and depth perception, for example, commonly involved an understanding of the geometrical properties of objects in the environment, and corresponding spatial relationships of patterns of stimulation falling on the retina. These accounts were generally peripheral rather than central.

The epitome of this approach is presented in the first book of Helmholtz's Handbuch der Physiologischen Optik (1856), where the eye is treated as a fine optical system, similar to, but more flexible than, a camera.

Physiological work has also traditionally been spatially based. Examples of this approach are found in anatomical studies and work on receptive fields, cortical envelopes, geniculate stratification and topological projection of information in different neural structures. These studies have been concerned more with which channels are conducting information than with when the information is being conducted. They have provided a good explanatory bases for certain classes of visual phenomena, like size, shape, and distance, etc. but have not been particularly successful in explaining other classes of phenomena associated with contour, edge, brightness, and color, etc. There is a growing body of evidence now to suggest that these latter phenomena can be better explained on a time basis.

Concern with time as a variable began in the nineteenth century. Color phenomena induced by the spinning of toy tops popularized the methods of intermittent photic stimulation as a temporal device for studying visual processing. The study of trains of photic stimulation is concerned with pulse durations and inter-stimulus intervals, but it is also concerned with harmonics, that is, with periodic visual phenomena which arise from cyclic characteristics of the train. Several classes of color phenomena are associated with flicker:

(1) Subjective Color Phenomena. Prevost, Fechner, and Benham demonstrated that various hues and saturations will arise from full spectrum stimulation under certain conditions of intermittency (in Cohen and Gordon, 1949).

(2) Brightness Enchancement (BE, The Brücke-Bartley effects). Under certain conditions an intermittently illuminated target will appear brighter than a steady target of the same intensity (Bartley, 1938; Brücke, 1894).

(3) Hue Shift (HS). Under photic intermittency hues will shift in specifiable directions depending upon the rate of intermittency and the wavelength (Ball and Bartley, 1965; Horst and Muis, 1969; Nilsson and Nelson, 1971).

(4) Desaturation (DES). Part spectrum targets will appear to lose their color under certain conditions of photic intermittency (Bartley and

Nelson, 1961; Ball, 1964).

The differences between color under steady light and color under intermittent light are analogous to differences in illuminant and reflected color spaces. Bartley (1958) pointed out that color experiences depend to a certain extent upon the mode in which the information is presented. Brown and black, for example, are easily produced in the reflected mode through mixing pigments; however, they are impossible to produce in the illuminant mode by mixing colored lights unless a surround-annulus configuration is used. As well as illuminant and reflected modes, Bartley (1958) and Katz (1935) suggest that there exists also an aperture mode, a volumetric mode, a film mode, and a temporal mode of presentation each of which produces slightly different color experiences.

Isolated studies in various classes of time related phenomena have been conducted for over one hundred years, but Bartley and his colleagues were the first to systematically investigate an extended range of phenomena related to flicker. They have organized and interpreted the findings within a temporal framework called the Alternation of Response Theory.

THE ALTERNATION OF RESPONSE THEORY

The Alternation of Response Theory proposes that the visual system consists of a number of parallel channels or longitudinal circuits which connect the peripheral receptor elements with higher centers in the nervous system. In the optic nerve, a single fiber is a functional unit and therefore constitutes a channel. At the retinal level, complex anatomical interrelationships involving bipolar, amacrine, and horizontal cells complicate the histological delineation of a channel, but functionally it is a restricted tissue system connecting the eye and the brain. The significance of this theory for the present research can be summarized by three concepts: periodicity, alternation, and reorganization.

The concept of periodicity evolved from the work of Bartley and Bishop (1932, 1933) on electrical stimulation of the optic nerve in the rabbit. They discovered that the visual system was periodically receptive to stimulation. The duration of the receptivity cycle was about 100ms.[3] As periodicity relates to the total pathway, or to cells in the cortex, it is considered a cortical excitability cycle. As it relates to activity in a single channel, it can be considered an activity-recovery cycle.

Under steady illumination, the channels in the visual system are in a state of alternation. Some are conducting information while others are recovering.

Different sequences of biochemical reactions are involved in these processes and time differences in discharge latencies, conduction rates, and recovery rates in different channels provide the mechanism for alternate firing and recovery of the various pathways in the system. These time differences can be explained at an anatomical level in terms of structural differences in the fibers such as length, diameter, myelination, number and properties of synapses, etc., or at a more atomistic level in terms of biochemical reactions in the pathway. The existence of these time differences in patterns of mass discharge forms the basis for the concept of alternation.

The waveform of the cortically evoked potential produced at the onset of a train of photic stimuli typically shows an early peak of maximal amplitude, which is followed by several smaller irregular peaks. Eventually the waveform exhibits a sequence of regular peaks whose periods are consistent and whose amplitudes are greater than those of the irregular peaks, but not so great as that of the initial peak. The temporal explanation for this waveform is that prior to stimulation, the visual system is in a state of relative quiescence. Since most of the channels are at rest at the time of initial stimulation, they are capable of relatively synchronous response. The simultaneous firing of large numbers of fibers accounts for a summated response to the stimulus which is represented by the first wave of the evoked potential. As various channels discharge and recover at different rates, patterns of neural activity are distributed over time and a certain duration elapses before synchrony of discharge becomes optimal. This period of irregular activity which precedes synchronous discharge is referred to by Bartley as the period of reorganization.

According to the alternation theory, certain conditions of stimulus intermittency program the channels to fire and recover synchronously, and thus produce bunching of activity in the optic tract. This disjunctivity of input is purported to be the cause of the various phenomena associated with flicker. The physical conditions for optimal synchrony of discharge or maximum bunching in the system can be specified by the interaction between the rate of stimulus intermittency and the on-off ratio or pulse-to-cycle fraction (PCF). Five to ten Hertz and 0.25 PCF are in general considered optimal conditions for this bunching.

These conditions have been demonstrated to produce optimal increases in brightness (Bartley, 1958; Rabello and Grüsser,1961; Ball and Bartley, 1968; Nelson and Bartley, 1961); optimal hue shifts (Ball and Bartley, 1965; Nilsson and Nelson, 1971; Horst and Muis, 1969) and optimal changes in saturation (Bartley and Nelson, 1961; Nelson, Bartley, and Ford, 1963; Ball, 1964).

The special virtue of the temporal mode of analysis is that neural activity lends itself well to quantification in terms of latencies, rates of dischange, and recovery times. The results of these time variations can be measured precisely and tend to reflect the operation of the nervous system in a nativistic way. Temporal approaches are not without limitations, however. One major criticism is that the mathematical parameters of time, for example duration and frequency, have structured temporal analyses to deal with successive events only at the expense of simultaneous events. Another criticism is that temporal approaches are too parsimonious. They attempt to explain a lot of complex neural activity in terms of a few simple parameters of a single variable.

Like wavelength theory, this temporal model is highly specialized. It was not meant to be universal. Despite its specialization, it offers a very important alternative way of studying visual phenomena which have not been adequately explained by the spatial theories. It provides a unique opportunity for investigating neural dependencies between hue, brightness, and saturation through studying concomitant changes in these dimensions under photic intermittency.

EMPIRICAL BACKGROUND

Temporal studies have been instrumental in recent attempts to break the neural color code. Much of the relevant work has been done on changes in hue under photic intermittency. Desaturation has been considered only recently, and only as an adjunct to hue shift. No optical system or methodology has been designed primarily and specifically to study desaturation, either in isolation, or in context with hue, brightness, or whiteness.

The basic questions of dimensionality remain unanswered:

Is color tridimensional? Does saturation have a coding process separate from those of hue and brightness? If not, to what extent is it related to each, and to whiteness?

Ball and Bartley (1965, 1968) studied phenomenal changes in brightness, hue, and saturation under intermittent conditions. They found that brightness varies with the rate of intermittency and PCF, but not generally with wavelength. BE appeared slightly greater near 520nm but in general appeared to be independent of wavelength. Changes in hue and saturation, however, depended upon wavelength as well as the conditions of intermittency (figs. 1 and 2). Both the direction of HS and the magnitude of DES are specifiable in terms of wavelength.

HS and DES were studied separately and under somewhat different conditions, but an important commonality in the findings suggests that they are fundamentally related. The spectral loci of the maximum and minimum points of desaturation (490 and 575nm) are the same as the points where HS either reversed direction, or was not apparent. Furthermore, the direction of HS in other spectral areas seems to be away from highly desaturated colors, and towards colors which remained saturated under photic intermittency. This commonality has been obscured by the separation between these studies and was never explained. It has important implications for the relationship between hue and saturation.

Nilsson and Nelson's (1971) findings corroborate this commonality. In comparing HS phenomena with the Bezold-Brücke effect,^{0} they found a third spectral locus where HS does not occur. It falls near Ball and Bartley's second desaturation maximum (near 630nm). When HS is rectified and short wavelengths are separated from the long ones at 575nm, the magnitude of HS across wavelength appears in a general way to be reciprocally related to the magnitude of DES.

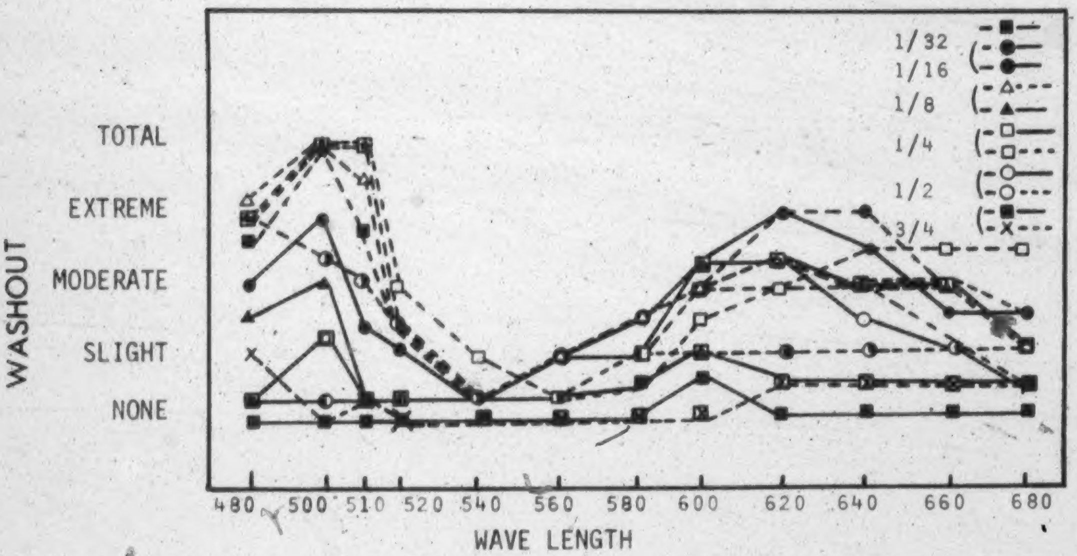

Figure 1. Wavelength plotted against temporally induced desaturation for various pulse-to-cycle fractions. (Ball and Bartley, 1965)

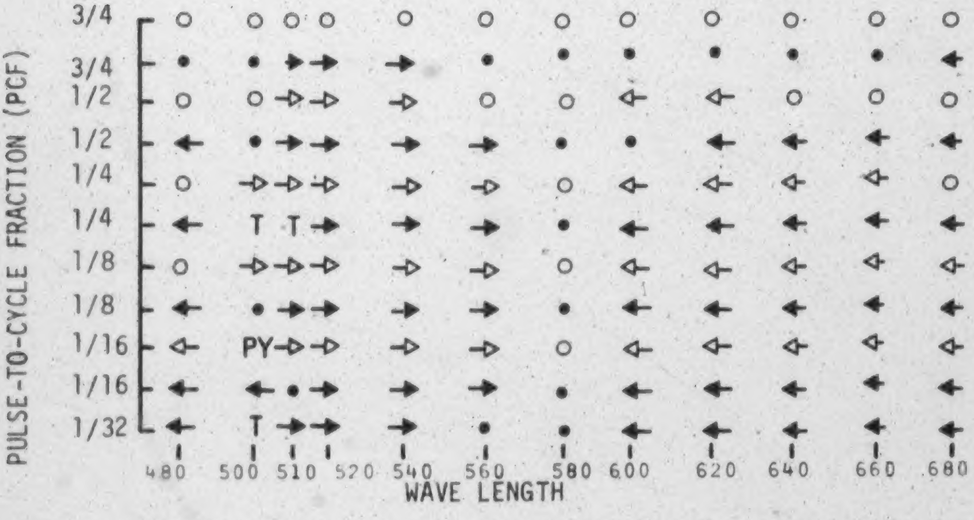

Figure 2. Wavelength plotted against temporally induced hue shift for various pulse-to-cycle fractions. (Ball and Bartley, 1965)

These data were collected under different conditions, at different times, and by different investigators, however, they suggest that under the abnormal conditions of photic intermittency, saturation is related more closely to hue than to brightness.

MacDonald (1971) suggested that hue and saturation are different experiential end results of a general chromaticity system. He proposed an harmonic-type mathematical model to account for the apparent interdependence of HS and DES in terms of a single neural process in the visual system. In his model, whiteness and saturation are related as differences in magnitude of a single chromaticity process. Whiteness and DES are considered to be "noise" in the system (probably in the LGN) which arises as the aharmonic result when overloading occurs in specialized color processing systems.

The model is based on a proposed temporal tuning mechanism wherein each color system has a temporal range within which it can effectively process information. For trichromats, each system is tuned somewhere in the midrange, for evolutionary or adaptive reasons, or whatever. This provides maximum processing flexibility under steady illumination. Under photic intermittency temporal tuning is disrupted. As discharge and recovery of the channels tends to synchronize, certain biochemical processes do not get enough time to regenerate. Neural overloading results and the point of optimal effective processing shifts within the temporal range of that system. Bi-lateral changes in hue and saturation are dependent upon the direction of displacement of the temporal tuning locus, which in turn depends upon the conditions of intermittency. For dichromats, the locus of tuning under steady illumination lies in a position within the range which is different from that of the trichromats. Under certain conditions of intermittency, this locus tends to shift toward its trichromatic counterpart.

Thus, the model purports to account for HS and DES in color defectives as well as normals. It is outlined here only briefly , but is presented in detail in the disucussion.

The purpose of this research is to clarify the concept of saturation in the context of dimensionality through the testing and development of this model.

The model offers an important alternative to the traditional (spatial) theories of color since (A) neither the Helmholtz nor Hering approach successfully accounts for color, especially for saturation; (B) neither traditional approach attempts to account for both color deficiencies and for trichromatic vision within the same context; and (C) there is, at present, no other extensive temporal explanation for color. Existing time-based models have dealt predominately with brightness rather than with hue and saturation. Under photic intermittency, changes in hue and saturation are consistent and specifiable. They tend to reflect the operation of the visual system in a way which spatial approaches cannot. It is these changes which are investigated in the present research.

METHOD

Experimental methodology was designed to study saturation in relation to brightness and hue under photic intermittency. The majority of the data were collected by psychophysical forced-choice or matching techniques. Preliminary tests involved training subjects and mapping ranges of HS and BE for several parameters in order to test the efficacy of the system, and to establish psychophysical ranges where saturation changes occur in relative isolation from HS and BE.

SUBJECTS

Five students served as observers in the main study. All were emmetropic and in their twenties. Four (DN, MG, SM, and BJ) were normal trichromats. GT was strongly deuteronomalous. A sixth observer, AJ, had Retinitis Pigmentosa. He was examined in an auxiliary study (See Appendix II).

APPARATUS

Since the methodology involved in this research cannot always be conveniently categorized into hardware

And software, certain procedural aspects are presented in the apparatus section.

Stimulus

A small (2mm) bi-partite field of bright homogeneous monochromatic light was presented to the right fovea. Wavelength, intensity, rate of intermittency, and PCF could be controlled independently in each half of the target.

Stimulus Delivery System

Parallel optical systems were used to project each half of the target (fig. 3). Each system was comprised of a tungsten light source, a double grating monochrometer and Maxwellian view optics. Episcotisters provided the photic intermittency.

Detail and Specifications

Lamps. Two tungsten filament (quartz iodine) sources were used. They were Bausch and Lomb step-down transformer lamps (Cat. No. 33-86-39).

Monochrometers. Two double grating monochrometers provided wavelength control. They were Bausch and Lomb digital counter units with slit height of 10nm and band pass of 2.0nm, tolerance of ± 0.1nm., and a

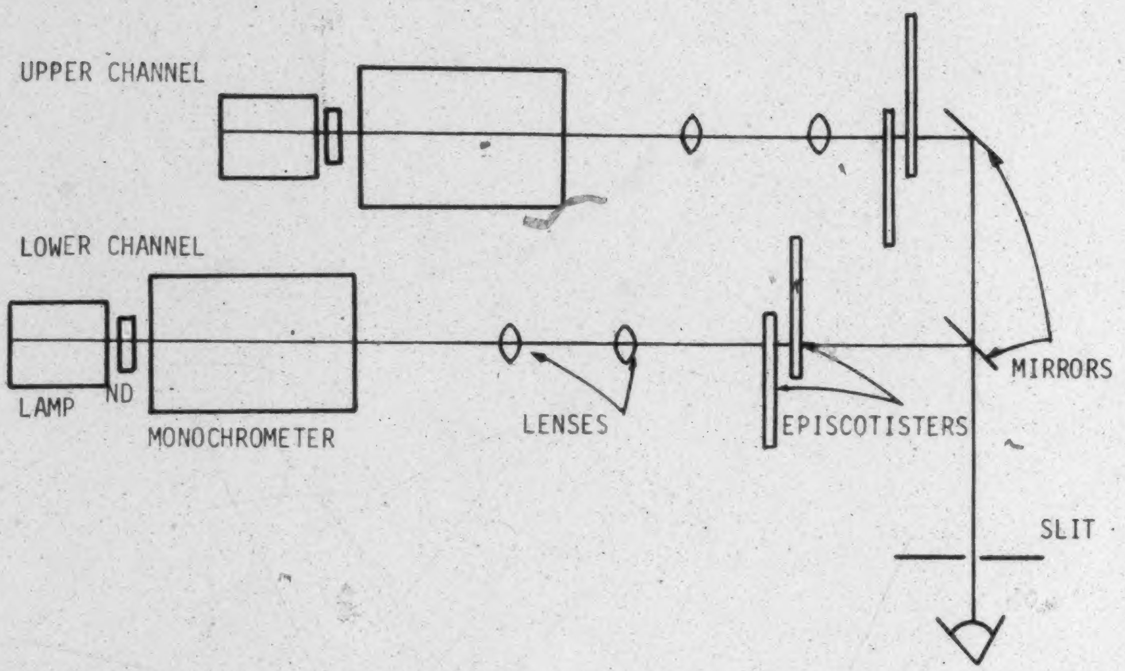

Figure 3. Diagram of optical system.

focal length of 250mm (Cat. No. 33-86-66).

Optics. Sequences of Edmund Scientific Co. achromatic condensing and collimating lenses were positioned downstream from the focal points of the monochrometers. The beams were reflected from front surface mirrors onto the retinal target area.

Intermittency Conditions. Intermittency was provided by three synchronous motors set at 5 Hz, 1 Hz, and 0.16 Hz and by a variable speed motor with a range from 0.4 Hz to 1.65 Hz. These motors carried black cardboard episcotister discs and were positioned to chop the collimated beams before they were reflected from the mirrors.

Retinal Positioning of the Target. The positioning of the stimulus field on the retina was roughly stabilized by fixing the position of the cranial bone structure. Each subject had a wax dental impression "bite-board" made which was fixed to an immovable head frame device inside a shielded observation booth.

Stimulus Manipulation. The experimenter could manipulate conditions of intermittency, wavelength, and luminosity independently in both lower and upper beams. Wavelength was controlled by setting the digital monitors on the monochrometers. Luminosity was set and controlled by the use of Wratten neutral density (ND) filters which were placed upstream from the monochrometers. Ss could also adjust luminosity in a limited range by controlling the lamp output with variacs.* Rate of intermittency was controlled by a combination of the number of cutouts in the episcotister discs and the use of the appropriate motor to drive them. The PCF was controlled by varying the angular proportion of the cutouts in the episcotister discs.

PROCEDURE

Observers were hired and tested separately on 16 tests which occurred during twelve 30-50 minute sessions at two day intervals. The bi-partite target was presented under various conditions of intermittency, wavelength, and luminosity. Both fields were intermittent for some tests, but for most tests, only the lower field was intermittent. Observers either made forced-choice comparisons, or matched the upper and lower fields for brightness, hue, or saturation depending upon the test.

The first two sessions were preparatory. These were followed by a session for luminosity tests, two for hue shift, two for brightness, four for saturation and a final one for extra hue shift tests. Details are presented below. Deutan procedure was somewhat different and is presented separately.

A. TRICHROMATS

I. Preparatory Sessions

Several preparations were made prior to the test sessions:

(1) Acuity was checked and color vision was tested using H-R-R and Dvorine color plates.

(2) Dental impression boards were made.

(3) Ss were dark adapted and individual luminosity data were collected by the threshold method in order to equate luminosity across the spectrum in subsequent tests.

(4) The "dimensions" of hue, brightness, and saturation were visually and semantically defined in order to establish efficient language communications for instructional purposes. Temporally induced changes in these dimensions were then demonstrated under the conditions of intermittency, luminosity, and wavelength where they occur in optimal magnitude and isolation from each other. Observers were familiarized with these types of changes in a short

training period which involved forced choices between steady and intermittent targets.

TEST CONDITIONS

Before each test, Ss were dark adapted to a photopic level (5-7) minutes). Matching tests involved four repeated measures of each condition, whereas forced choice tests involved only two.

II. Luminosity Ranges

Lower luminosity thresholds were established at eight spectral loci (475, 500, 525, 550, 575, 600, 625, and 650nm) for changes in hue, brightness, and saturation which occur under 10Hz, 0.25 PCF. The lower (intermittent) field was compared with the upper (steady) field for each phenomenon as the level of luminosity in both fields was varied simultaneously over a wide range with ND filters. Thresholds differed for different phenomena and these data were used to experimentally isolate saturation changes in other studies (See Results section).

III. Hue Shift and Hue Matching

The spectral areas and directions of hue shift were determined under 10Hz, then 3Hz, 0.25 PCF first by forced choice between the intermittent and steady fields; and later through matching by the method of limits. In the forced choice test, S was asked to report whether HS was detectable, and if so, towards which end of the spectrum.

In preparation for HS tests, wavelength and luminosity were equated in both fields under steady light. Under 3Hz, slight BE occurred and was also compensated for in the matching tests before hue matches were made. BE effects were small as the luminosity range was not high (T+3 log units), and consequently, gross changes in luminosity were seldom necessary. E controlled most of these changes with ND filters, but some fine tuning was done by S with variacs.[6]

Test I: Direction of Hue Shift. Ss were instructed to compare fields for hue differences only and not for saturation differences. Direction of HS was mapped in 10nm steps from 700nm to 400nm with luminosity equated from 635nm to 475nm. Reports were verbal.

Methodological note: In certain parts of the spectrum hue and saturation changes are difficult to separate. For example, HS from orange to yellow can be misinterpreted as a desaturation effect as (A) desaturation usually occurs here anyway and (B) yellow looks more desaturated than orange under steady illumination. Guessing was discouraged here. Possible errors were subsumed under the category of hue shift in Test I and then separated out in Test II.

Test II: Magnitude of Hue Shift. Hues presented intermittently at 10Hz, 0.25 PCF were matched to steady hues by the method of limits at seven spectral loci. They were:

(1) 650 and 545nm where positive HS (i.e., toward longer wavelengths) was expected;

(2) 620, 580, and 515nm where no appreciable HS was expected; and

(3) 600 and 475nm where negative HS was expected.

Luminosity was adjusted accordingly as the wavelength was changed.

Further magnitude HS tests were done after saturation data were collected. These were designed to compare HS magnitude with DES magnitude. They involved:

(1) A split-beam comparison of HS magnitude in adjacent spectral areas where S made simultaneous subjective comparisons of 475 x 495nm, then 530 x 545nm, 545 x 563nm, 587 x 600nm, 600 x 610nm and 650 x 635nm under the same conditions of intermittency.

(2) An intensive hue matching study where spectrally closer wavelengths and 10 repeated measures were used: The wave lengths were: 475, 495, 510, 530,

545, 560, 580, 587, 600, 610, 620, 635, and 650nm.

IV. Brightness Studies

Brightness changes were studied under intermittency at 3 non-HS wavelengths (620, 580, and 515nm) first in a lower luminosity range (Threshold +3 log units) where saturation changes were studied and later in a range (Threshold +4 log units) where both BE and DES occur.

(A) Saturation Level Brightness

Test I Rate x PCF. Brightness was mapped over 13 rates of intermittency (1, 2,...,10, 15, 20Hz, and fusion) for each of four PCFs (0.125, 0.25, 0.50, and 0.75). Ss were instructed to compare the brightness under each rate of intermittency first with that of the steady target, and later with the brightness under the next highest rate when both fields were intermittent (that is, 1 x 0, 2 x 0, 3 x 0, etc., then 1 x 2, 2 x 3Hz, etc.).

S was instructed to report whether the lower target appeared brighter, less bright, or equal to the upper target. The magnitudes of brightness changes and the shapes of the rate curves were roughly determined by making additional comparisons of certain rates with others which were optimal for brightness changes, and with Talbot level conditions (see Table 8).

__Test II PCF.__ Brightness was then tested as a function of PCF with rate and wavelength held constant. All combinations of 0.125, 0.25, 0.50, 0.75, and steady light were compared for 3 wavelengths and 3 rates: 3 Hz, 10 Hz, and fusion.

__(B) Brightness Enhancement Level__

BE at T + 4 log units was studied as a function of wavelength at 10 Hz and 0.25 PCF by ordinally comparing brightness in adjacent spectral areas during a split beam test. Luminosity was first equated across the spectrum under steady illumination, and then BE data were collected as wavelength was varied in nine 25nm steps from 450nm to 650nm.

V. Saturation Studies

Saturation was studied as a function of photic intermittency in a luminosity range (T + 3 log) where BE and HS do not ordinarily occur, and for 3 spectral areas (620, 580, 515nm) where HS does not occur. Luminosity was equated across the spectrum and ordinal data were collected by the same method used in the brightness studies above. __S__ was instructed to report whether the lower target appeared more saturated, less saturated, or equal to the upper target.

Test I: Rate x PCF. Luminosity was further adjusted to compensate for brightness changes under intermittency (particularly for BE under low rates of intermittency). Saturation was mapped over 14 rates of intermittency (1, 2,...,10, 12, 15, 20Hz, and fusion) for each of four PCFs (0.125, 0.25, 0.50, and 0.75) in the same manner that brightness was mapped out. All combinations of PCFs were compared, but the shapes of the rate curves were determined by using only three of the remaining rate permutations (6 x 10, 5 x 12, and 4 x 15Hz).

Test II: Supersaturation. An increased saturation effect occurred at low rates of intermittency. The temporal extent of this effect was established by observing saturation changes at very low rates (0.16, 0.25, 0.33, and 0.50 Hz) and under the same PCF and wavelength conditions which were used in the previous study. Under these rates, inter-pulse intervals were long enough that a single pulse occurred within each cycle. BE was adjusted for and Ss were asked to report saturation differences in the upper and lower targets at the beginning of each cycle, and to note whether saturation changes occurred in the lower target within the duration of the cycle.

Test III: PCF. Saturation was then tested as a function of PCF with rate and wavelength held constant. All PCF combinations of 0.125, 0.25, 0.50, 0.75, and steady light were compared for each of 3 wavelengths x 3 rates: 3 Hz, 10 Hz, and fusion.

Test IV: Saturation x Wavelength in a split-field study the magnitude of saturation change was compared in adjacent spectral areas under 3 Hz, 0.50 PCF and under 8 Hz, 0.50 PCF. Wavelength was changed in eight 25nm steps from 475nm to 650nm. Three extra comparisons of optimal ranges were made when the optimal ranges were determined. They were 475 x 575nm, 575 x 650nm, and 515 x 625nm.

B. DEUTAN

The deuteranonalous observer went through much the same procedure as the trichromats. He was tested for luminosity, hue shift and hue matching, brightness, and saturation changes under photic intermittency. Procedural deviations from the normal trichromatic methodology are outlined here.

I. Hue Matches

Since GT had difficulty matching hues, especially in certain spectral areas, ranges of hue match rather than specific spectral points were collected under both steady and intermittent conditions.[7] As well as hue matches for steady light and 10 Hz, hue matching performance was tested as a function of rate of intermittency for 4 wavelengths (425, 500, 550, and 625nm). The rates of intermittency used were: 2.4, 3.5, 4.5, 5.8, 7.0, 8.0, 8.8, 10, and 15 Hz.

II. Brightness Studies

GTs brightness responses were studied only at saturation level luminosities. Procedure was the same as for trichromats except that more wavelengths were tested. They were 425, 475, 515, 550, 600, and 620nm.

III. Saturation Studies

Procedure was the same as for trichromats but again the above wavelengths were added.

RESULTS

The research was successful. The reliability of the methodology and of the optical system was established through the successful replication of major works done by Ball and Bartley (1965) and by Nelson and Bartley (1961) within the Alternation of Response Theory. All relevant phenomena including hue shift, brightness enhancement, and desaturation were produced and measured. The major findings are summarized below and a detailed description follows:

MAJOR FINDINGS

1. At rates below 3 Hz the intermittent target appeared more highly saturated than a steady target of the same wavelength, intensity, and brightness. This effect is called "supersaturation" (SS).

2. Luminosity thresholds exist for supersaturation and desaturation, and are lower than those for hue shifts and brightness enhancement.

3. In a general way, hue shift and saturation changes are inversely related, and can be accounted for by a single neurological mechanism.

4. Brightness enchancement seems to be exponentially related to luminosity. This relationship may involve a temporal tuning mechanism or some sort of

Weber fraction.

5. Parallel desaturation and supersaturation processes implicate temporal tuning mechanisms in the chromaticity system.

6. Hue matching performance in deutans can be facilitated or disrupted through temporal manipulation of photic input.

7. For deutans, the experience of saturation-desaturation seems to be related to the ability to match hues which suggests an imbalance in chromatic temporal tuning mechanisms.

Luminosity Functions (fig. 4)

The luminosity functions were normal. GT showed a curve typical for a deuteranomalous observer with a slight recession near 525nm and peak at a slightly longer wavelength than the trichromatic functions (550nm).

TRICHROMATIC DATA

I. Luminosity Study

Figure 5 shows luminosity thresholds for the occurrence of BE, DES, SS, and HS over wavelength at 10 Hz, 0.25 PCF. In general, brightness enhancement occurs

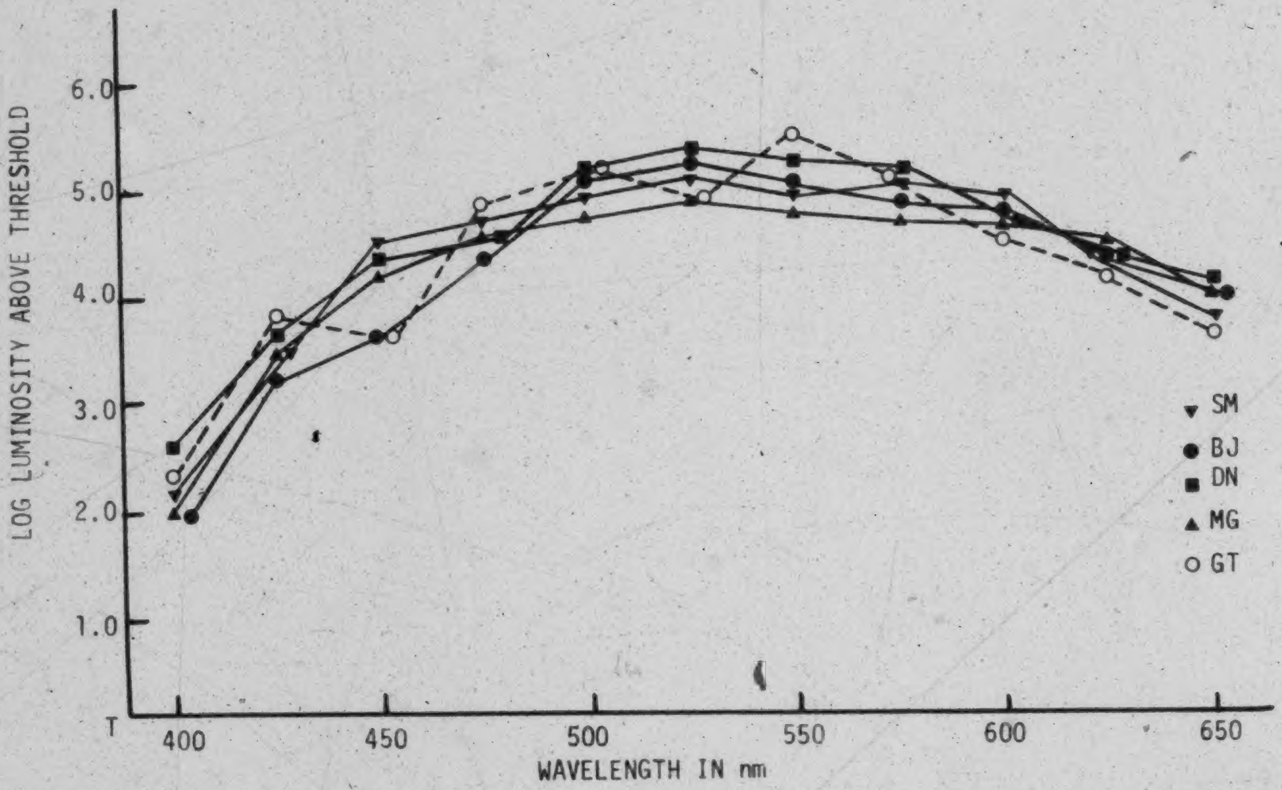

Figure 4. Luminosity as a function of wavelength.

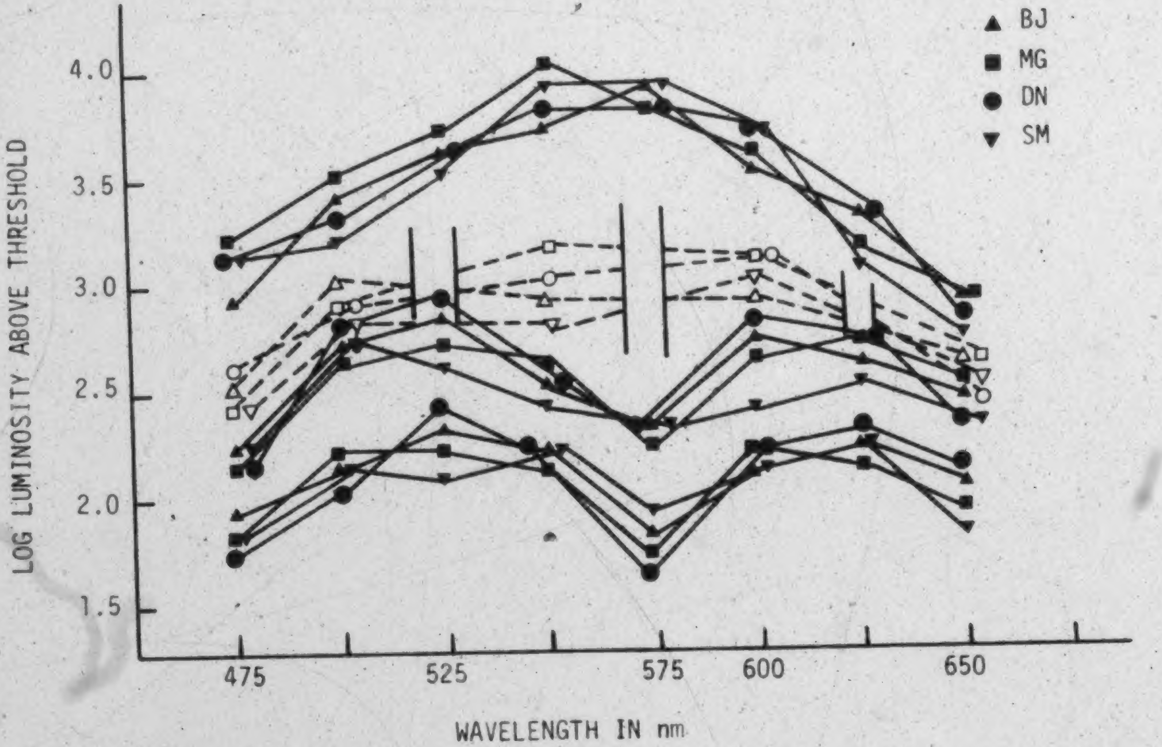

Figure 5. Luminosity thresholds for BE, HS, SS and DES as a function of wavelength (10Hz, 0.25 PCF).

in a high luminosity range (above T + 3 log units) whereas changes in saturation occur above T + 2 log units. Hue shifts occur in the midrange. These thresholds are lower at lower rates of intermittency and at higher PCF's. Thresholds for SS and DES vary similarly across wavelength but SS occurs at somewhat lower luminosities than DES. The shape of the BE curve follows that of the luminosity curves. These data were used to further separate the various phenomena through experimental controls in subsequent studies.

II. Hue Shift and Hue Matching

The directions and magnitudes of hue shift were consistent with the previous findings of Ball and Bartley (1965), Horst and Muis (1969), and Nilsson and Nelson (1971). Figure 6 shows verbal reports of direction of hue shift under both 3 Hz and 10 Hz. In the red end of the spectrum, S̲s reported positive hue shifts under 3 Hz and negative shifts under 10 Hz. This change in directionality is interpreted in this thesis as a possible saturation phenomenon which will be discussed later. Hue matching data for 10 Hz, 0.25 PCF confirm that the directions and magnitudes of HS are generally consistent with findings of previous studies (fig. 7). Three spectral areas exist where little or no hue shift was apparent (620-625nm, 570-580nm, and 505-520nm).

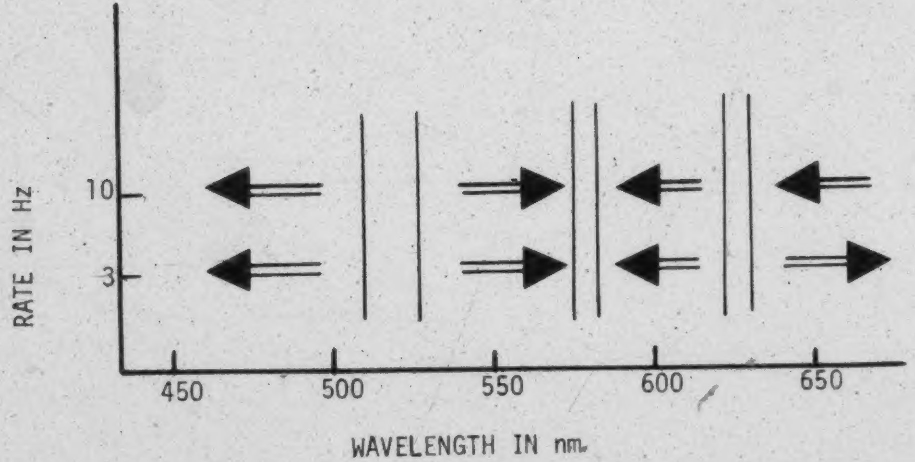

Figure 6. Reported direction of HS as a function of wavelength for 0.25 PCF.

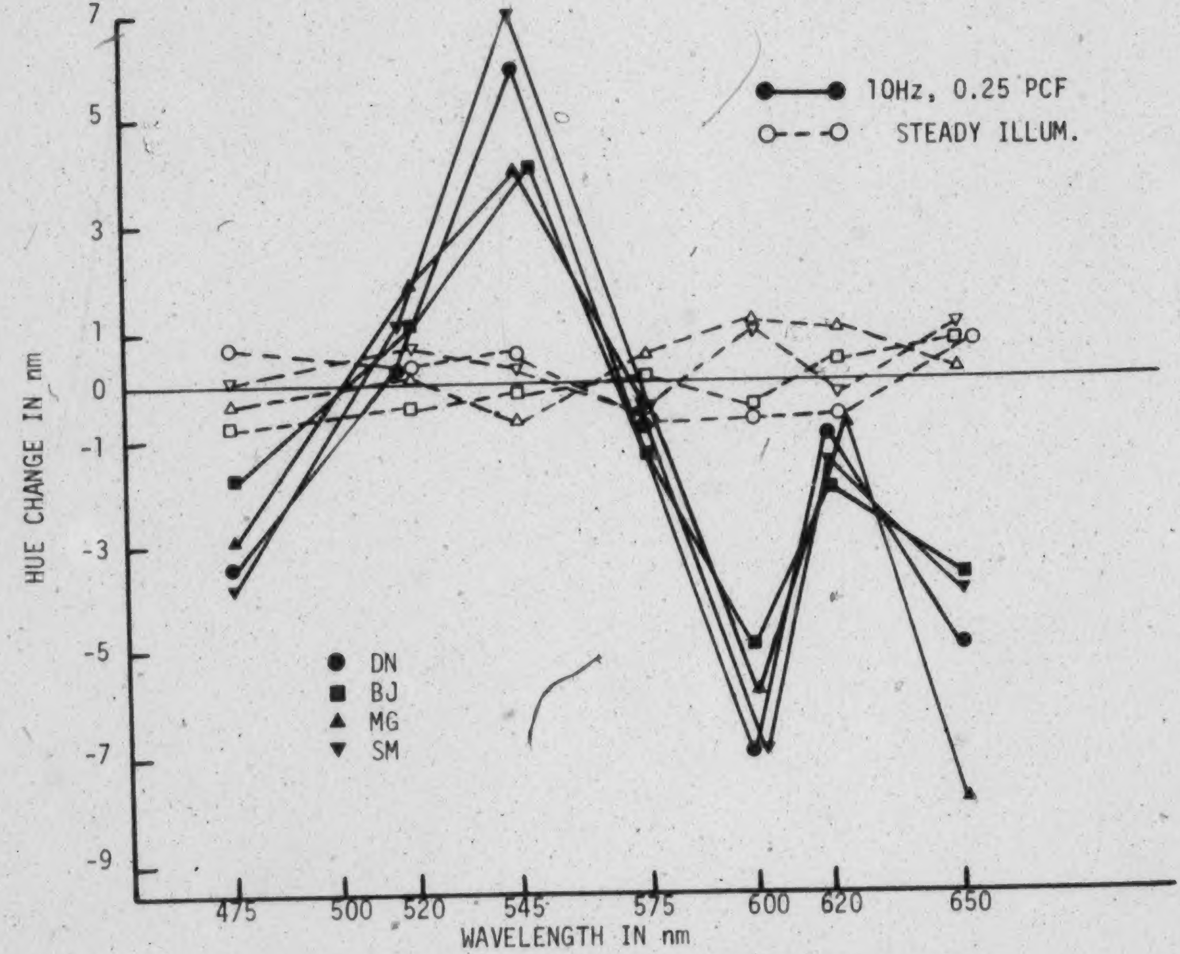

Figure 7. Hue matches as a function of wavelength.

wavelengths within these areas were selected as prime spectral loci for the saturation studies in order to isolate saturation changes from hue shifts. In figure 7, it appears that the magnitude of HS for any hue is related to the spectral distance of that hue from one of the three areas of no hue shift. This notion was roughly corroborated in a split-field study (fig. 8) where magnitudes of HS in adjacent spectral areas were compared simultaneously at 10 Hz and 0.25 PCF. This reciprocity between HS magnitude and spectral distance from the stable points was confirmed in a more rigorous hue matching study (fig. 9) where 10 repeated measures were taken for matches in intermediate spectral areas. It is important to note that HS magnitude is greater at 600 and 545nm than at 475 and 650nm.

III. Brightness Studies

Brightness was investigated first in a luminosity range (A) where saturation changes are isolated (T + 3 log units) and then in a range (B) where brightness enhancement interacts with saturation changes (T + 4 log units).

(A) Saturation Level Brightness

Figure 10 shows brightness as a function of rate and PCF averaged over repeated measures for 3 wavelengths.

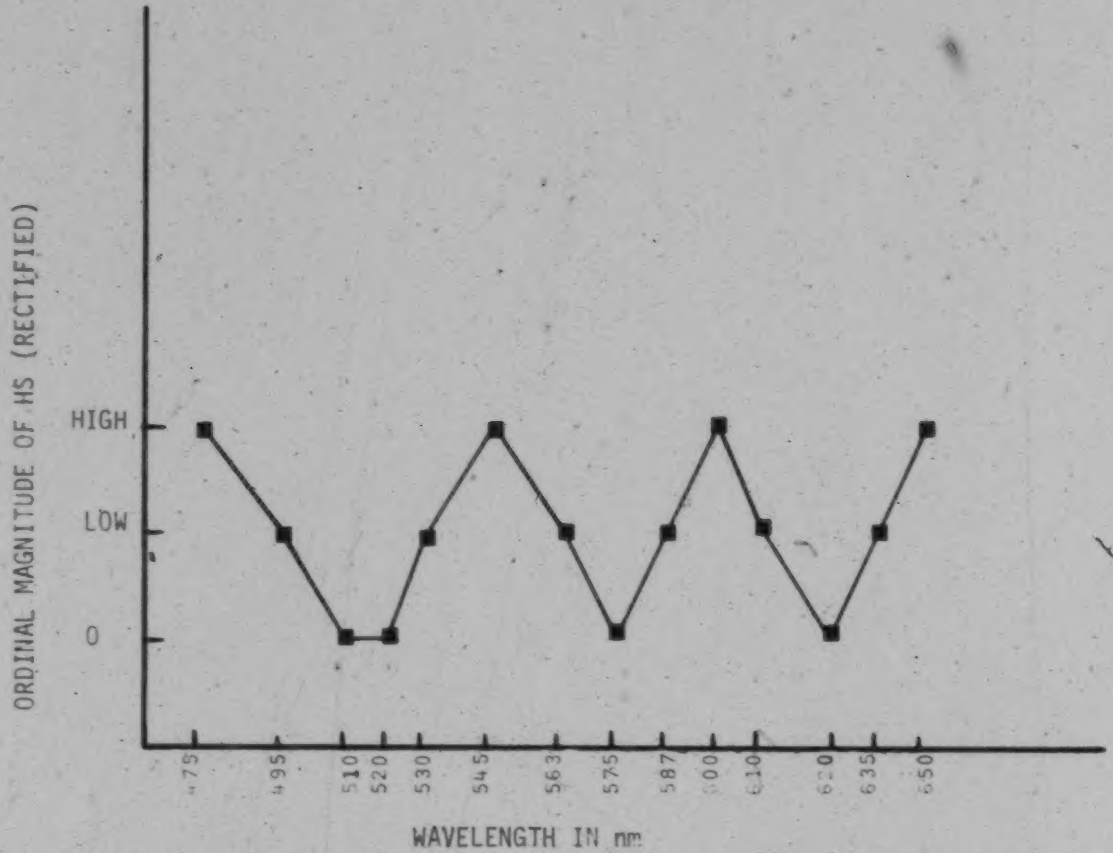

Figure 8. Compared magnitude of HS as a function of wavelength at 10Hz, 0.25 PCF.

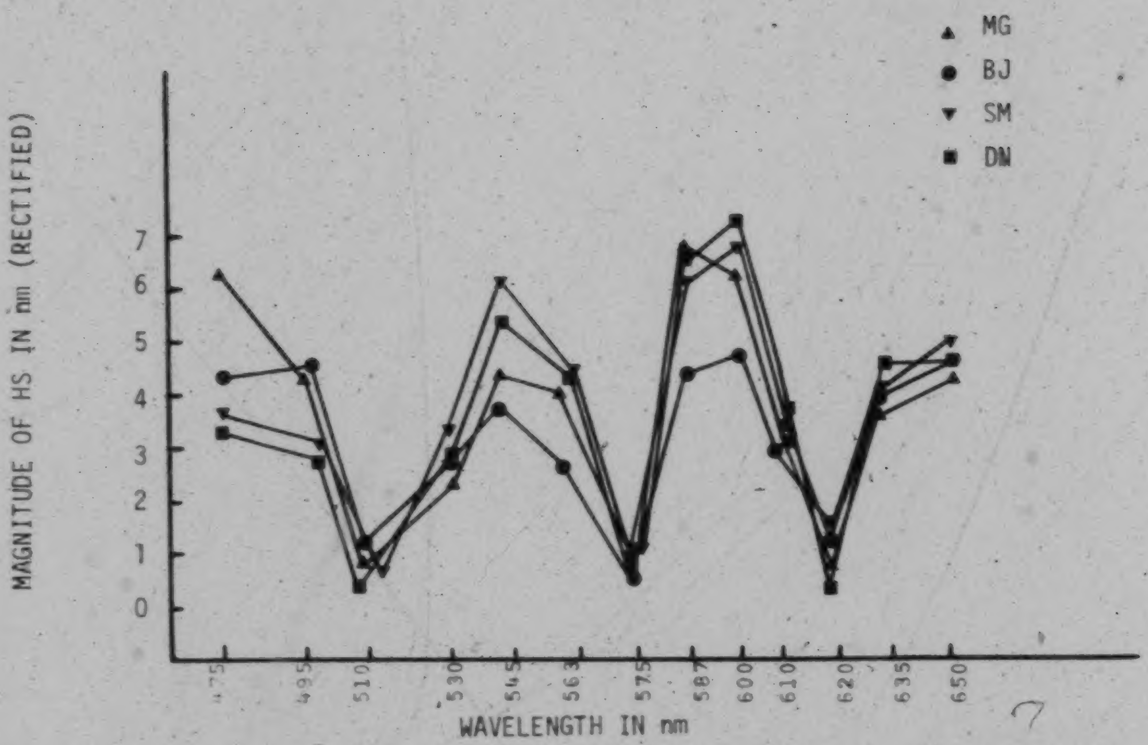

Figure 9. Magnitude of HS as a function of wavelength at 10Hz, 0.25 PCF.

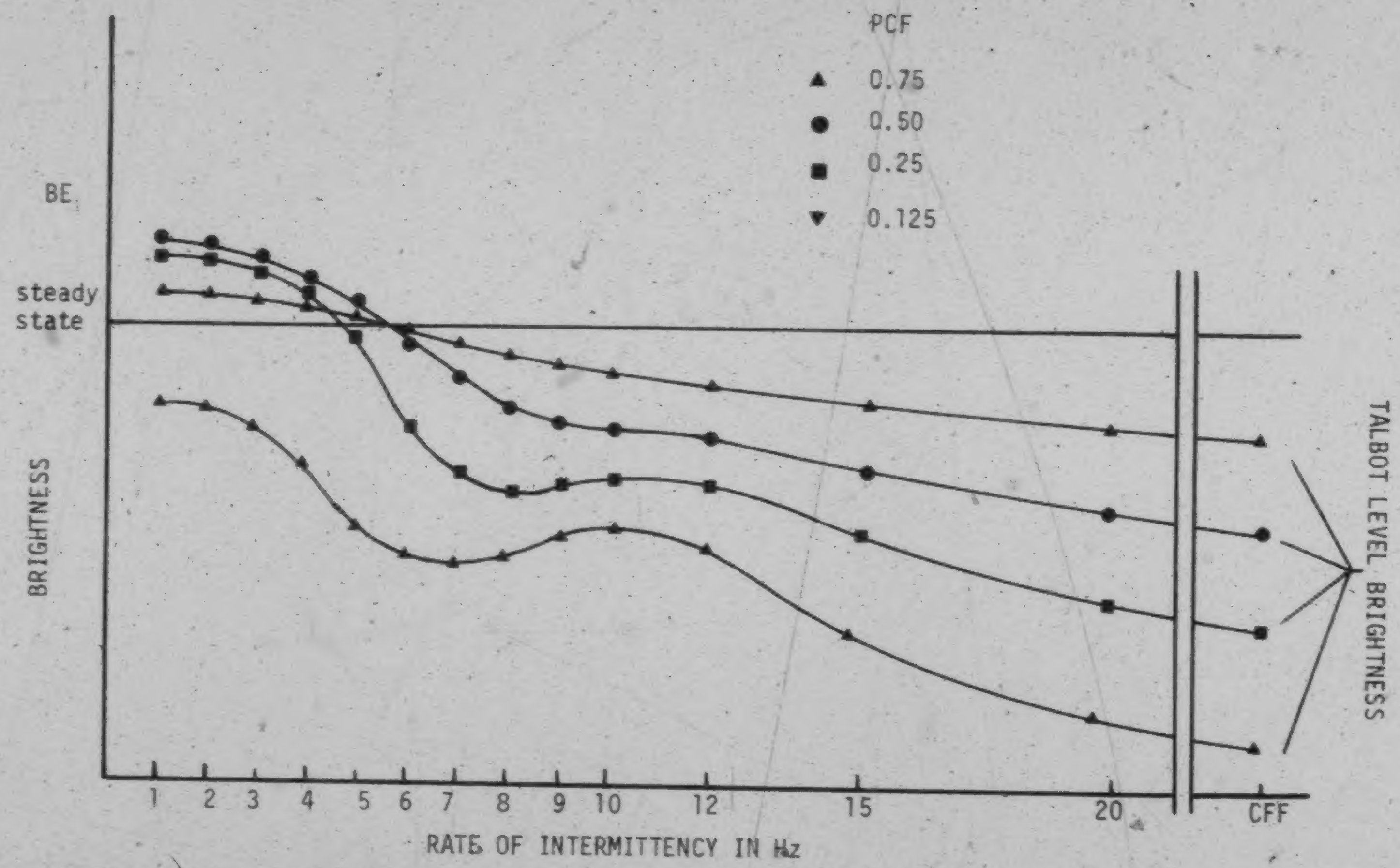

Figure 10. Brightness as a function of rate of intermittency (T + 3 log)

In a general way, brightness is proportional to the luminous flux (i.e., 1/PCF) with the exception of PCF 0.75 below 5 Hz. Slight BE is apparent at low rates but as rate increases, brightness approaches Talbot level for each PCF. This change is gradual and begins at rates much lower than CFF. Figure 11 illustrates this change in terms of brightness as a function of PCF. At 3 Hz, BE occurs and is optimal at 0.50 PCF. For 10 Hz and fusion however, brightness changes over PCF resemble Talbot level functions rather than BE effects. Luminosity of T + 3 log units was chosen specifically to minimize BE for easier interpretation of saturation change.

(B) Brightness Enhancement Level (T + 4 Log)

The shape of the BE function (fig. 12) suggests a monotonic relationship over wavelength between BE, luminosity (fig. 4), and BE threshold (fig. 5). However, since luminosity was equated across the spectrum prior to this test, the shape of the curve reflects a possible exponential relationship between BE and luminosity.

IV. Saturation Studies

Figure 13 shows change in saturation as a function of rate and PCF. Ordinal data were collected, but the direction of change was the same for 620, 580, and 515nm. Desaturation occurs under most rates, 8 Hz being optimal.

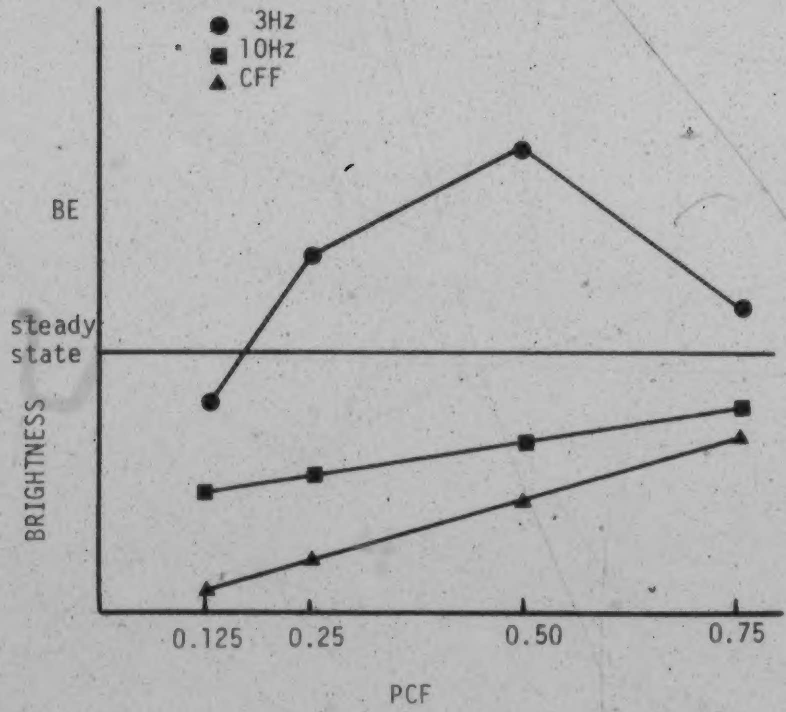

Figure 11. Brightness as a function of PCF (T+3 LOG)

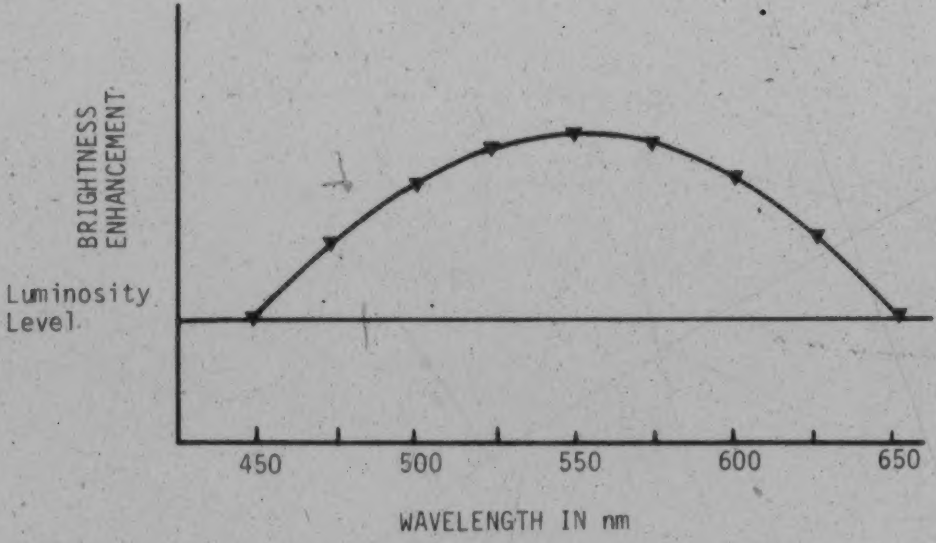

Figure 12. BE as a function of wavelength (T + 4 log)

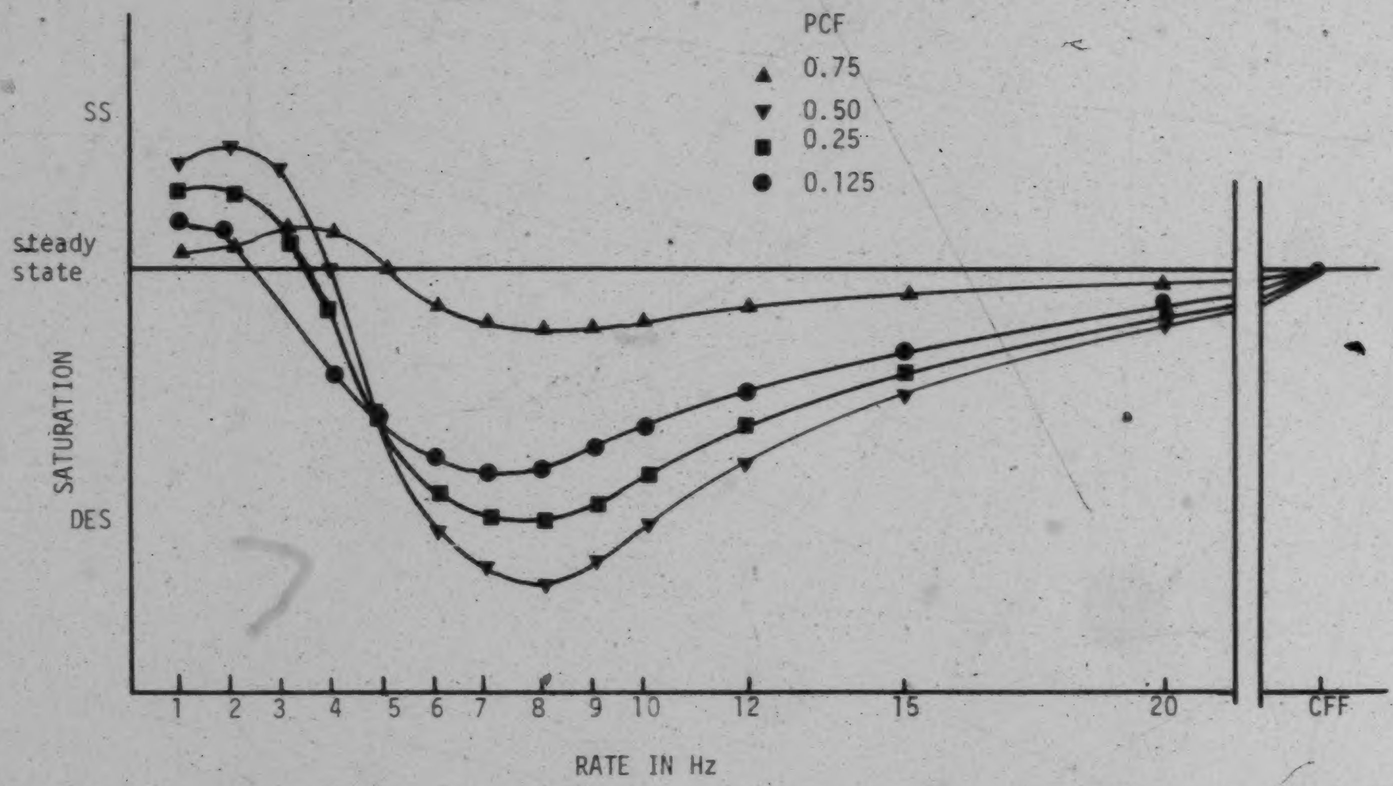

Figure 13. Saturation as a function of rate and PCF.

Under low rates (1-4 Hz) a "supersaturation" effect occurred. PCF 0.50 was optimal for both these effects. Supersaturation has never been reported before and has possibly been confused with brightness enhancement which also occurs at low rates. In this study, however, brightness was equated before saturation judgements were made.

The SS effect persisted over a wide luminosity range which included the BE threshold (see fig. 5).

Figure 14 shows saturation as a function PCF for 3 rates of intermittency. No change in saturation occurred at fusion but SS and DES change with PCF in mirror image fashion, 0.50 being optimal for both shifts.

Figure 15 shows the magnitude of both DES and SS as a function of wavelength. DES is bi-modally distributed over wavelength with maxima near 515 and 620nm, and a minimum point near 580nm. The shape of the DES curve resembles that of the DES threshold curve (fig. 5) and also the curve of Ball and Bartley (1965). In this case, however, the magnitudes and lateral (spectral) dispersions of DES about 515 and 620nm are the opposite. 620nm is the point of greater desaturation, and correspondingly narrower spectral range. SS appears to increase as a function of wavelength from blue to red.

Supersaturation Study

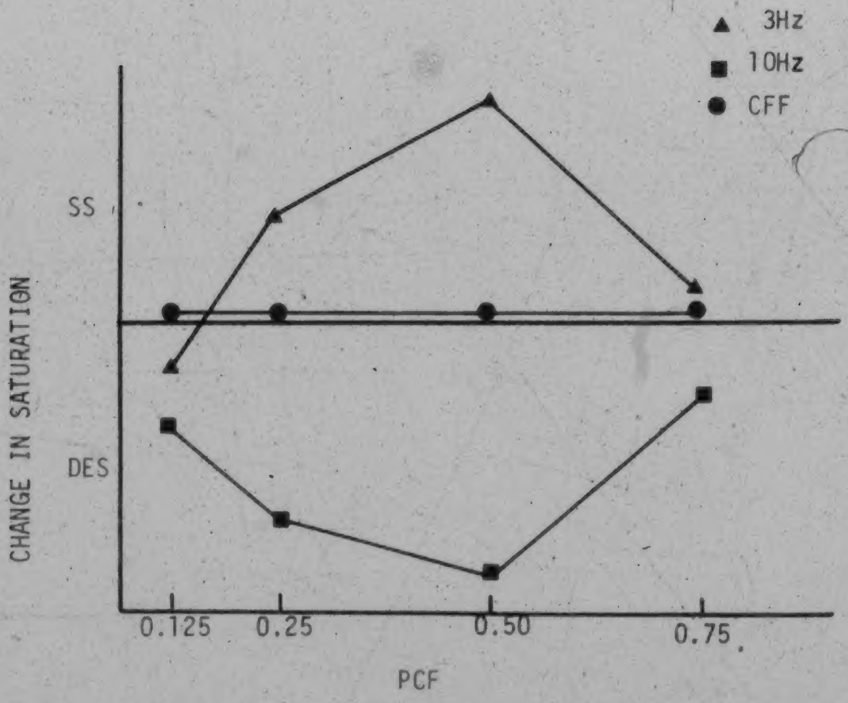

Figure 14. Change in saturation as a function of PCF ($\bar{x}$ OVER wavelength).

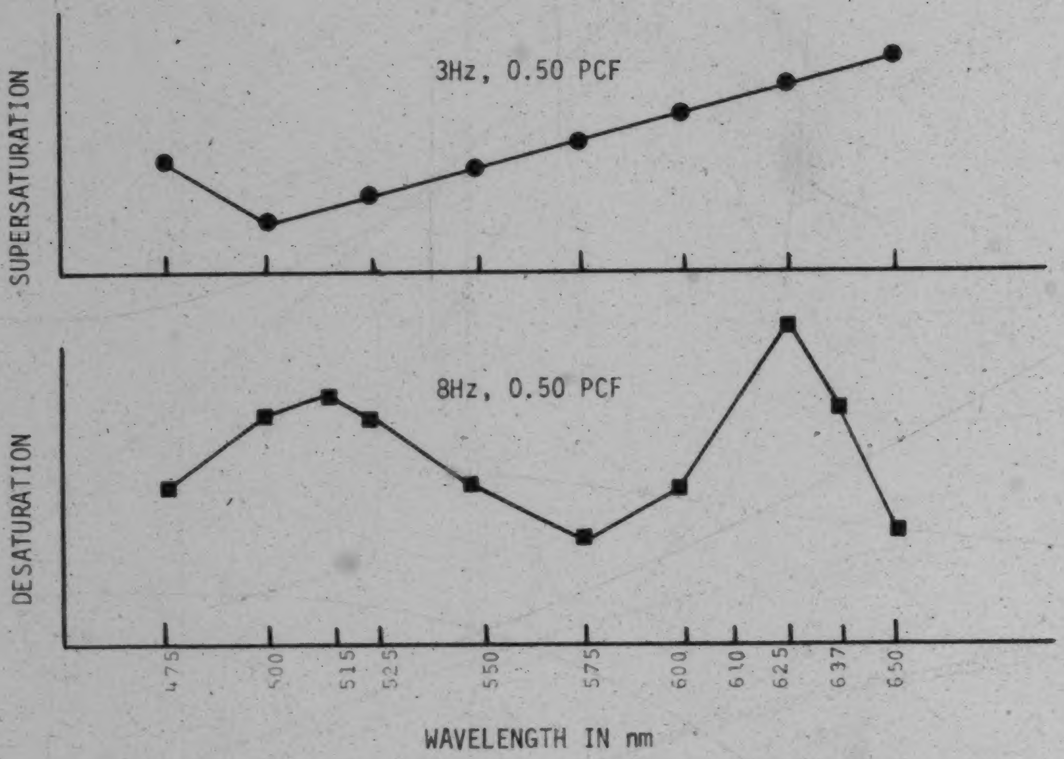

Figure 15. Magnitude of DES and SS as a function of wavelength.

Figure 16 shows the temporal limits for SS for 620, 580, and 515nm. For single pulse lengths up to 1000ms SS remains positive and constant for all three wavelengths. Above 1000ms SS diminishes observably for each, but decay times vary with wavelength, 515nm taking the longest (1250ms) to reach steady state saturation (interstimulus intervals between 75ms and 4500ms were tested). The minimum effective ISI for single pulse phenomena was 125ms. Above this, the length of the ISI influenced neither the onset time nor the decay rate for the SS effect (Table 14, Appendix I).

II. DEUTAN DATA

GT had a normal luminosity curve which is typical for a deuteranomalous observer (fig. 4). He also experienced changes in hue, brightness, and saturation, but under different conditions of intermittency than the trichromats. In most cases these changes were wavelength dependent.

I. Hue Shift and Hue Matching

Under steady illumination, GT made matching errors in all spectral areas, but performed more poorly near 550nm and 425nm than in other areas (fig. 17). Under

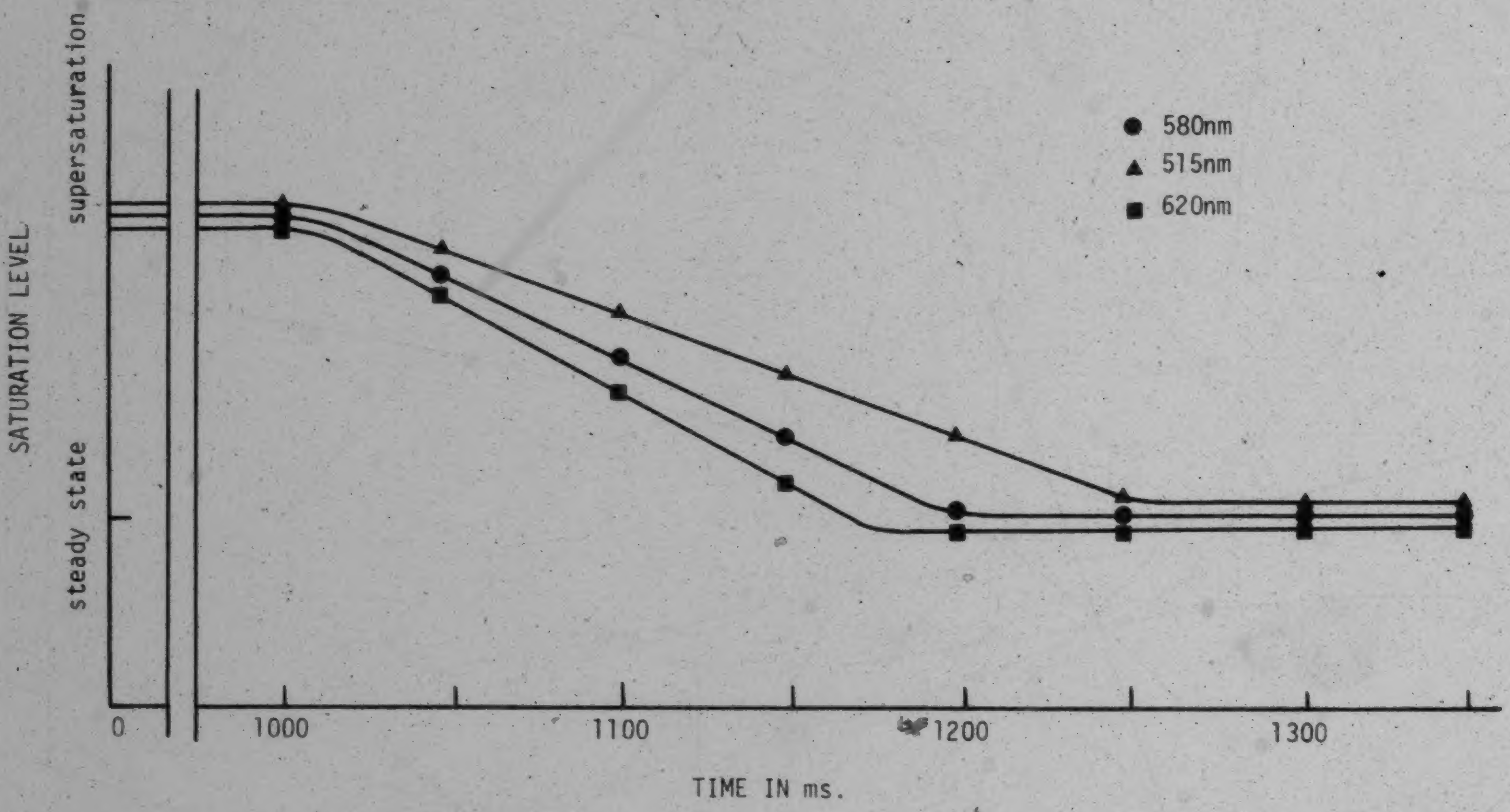

Figure 16. Supersaturation decay times for 620nm, 580nm, and 515nm.
(single pulses)

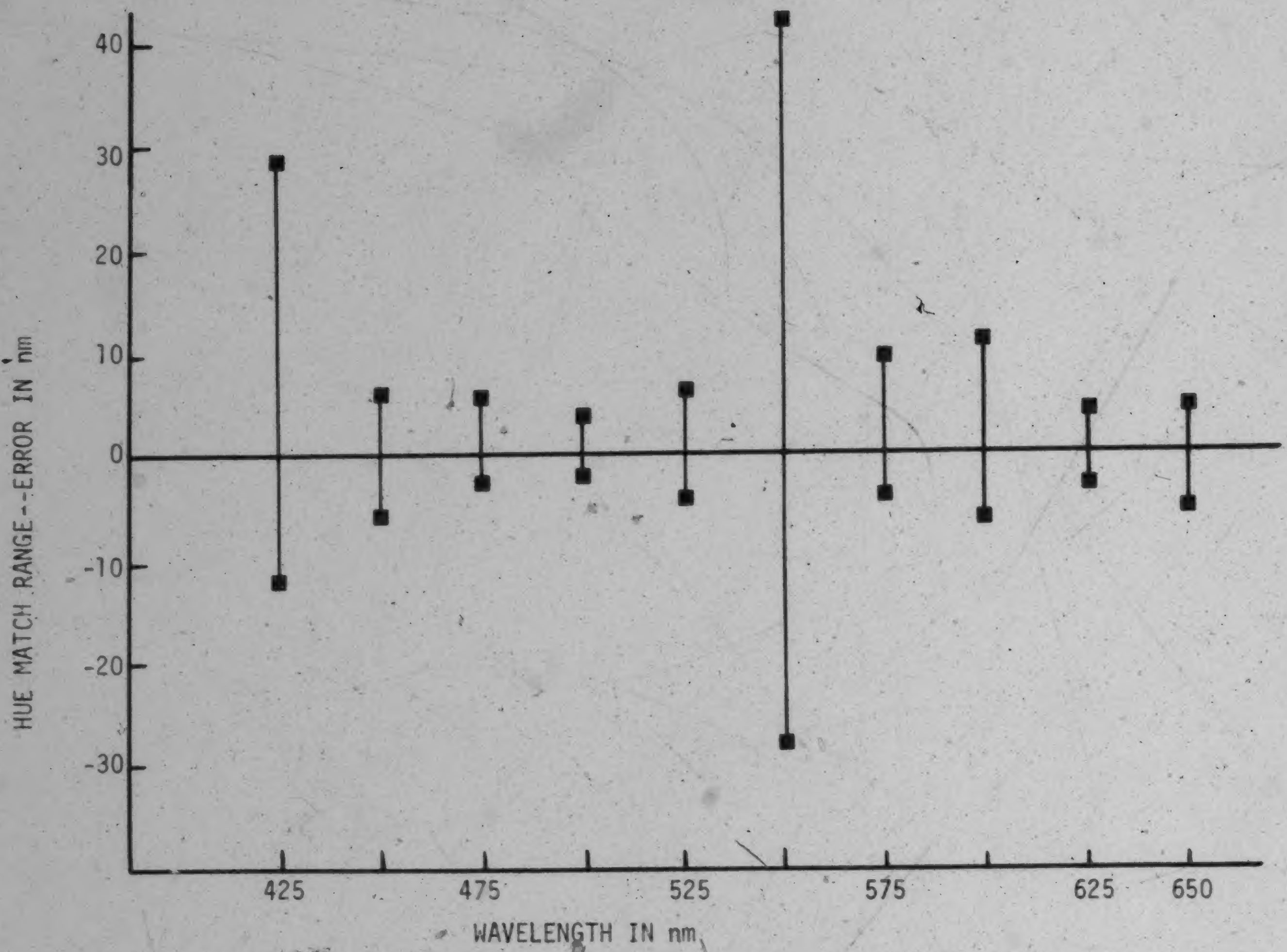

Figure 17. Deutan hue matches over wavelength for steady illumination.

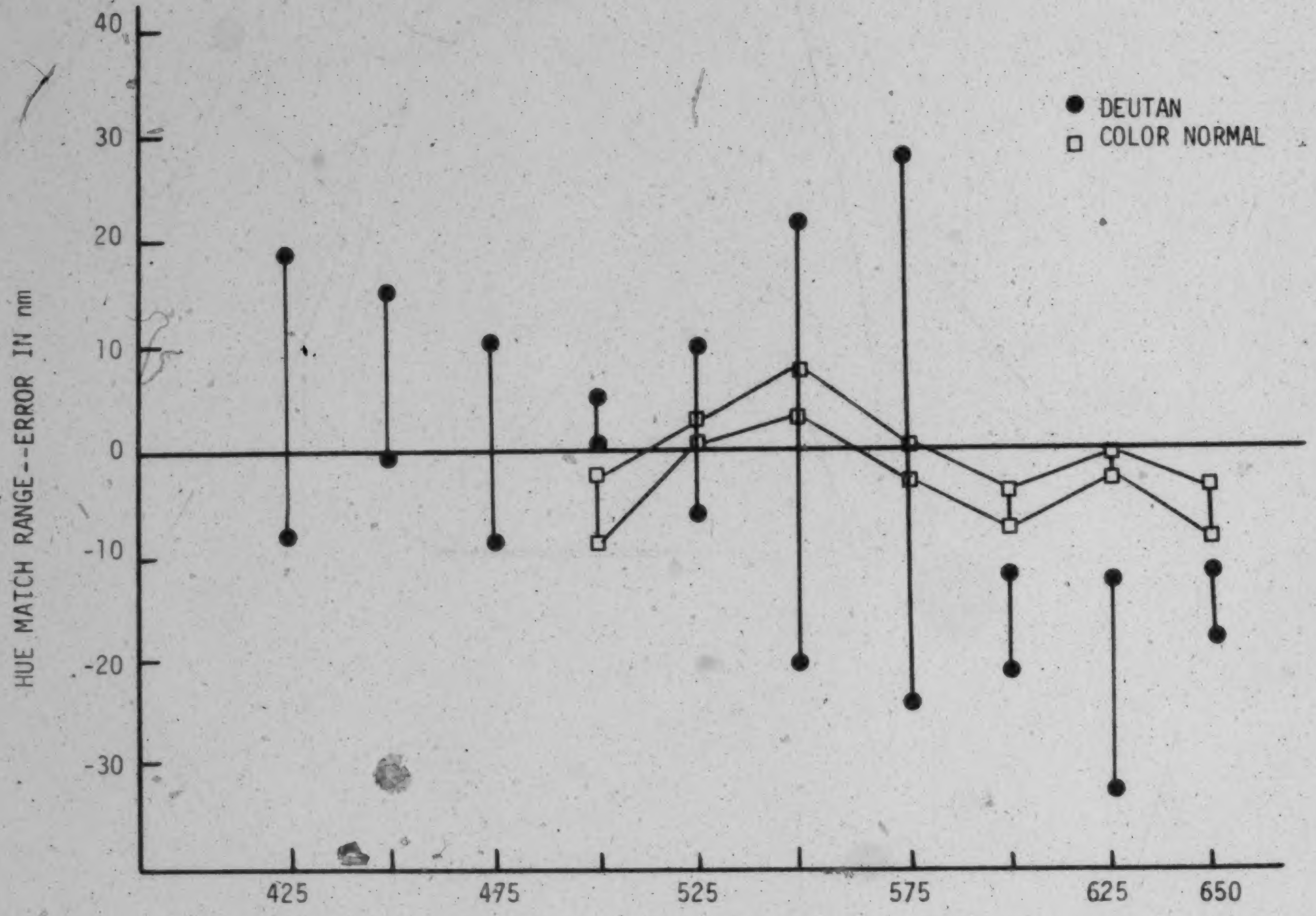

Figure 18. Deutan hue matches under 10Hz, 0.25 PCF as a function of wavelength.

intermittency of 10 Hz and 0.25 PCF his matches improved in these areas but worsened in others (fig. 18). Figure 19 shows the direction and magnitude of hue shift as a function of rate of intermittency for both well and poorly matched spectral areas. The directions and average magnitudes of hue shifts are similar to those for trichromats (fig. 7), but GT's range of errors was much greater and varied with wavelength. The shapes of the error envelopes for rate variations are similar for 425, 500, and 550nm, but the shape for 625nm is different (fig. 19).

This difference is more clearly represented in figure 20 where average ranges of matching errors in these four spectral areas are plotted as a function of rate. Curves for 425, 500, and 550nm show optimal matching performance in the midrange (7.0-8.8 Hz) whereas matching for 625nm was worse in the midrange, and better at low rates of intermittency.

Figure 21 shows that at 5.8 Hz, 550nm is somewhat better matched under PCF 0.50 than under 0.125, 0.25, and 0.75.

II. Brightness Studies

Figure 22 shows brightness as a function of rate of intermittency at T+2) log luminance for GT. BE was not apparent at this luminosity level, except at low rates of intermittency (below 3 Hz). In general, brightness is

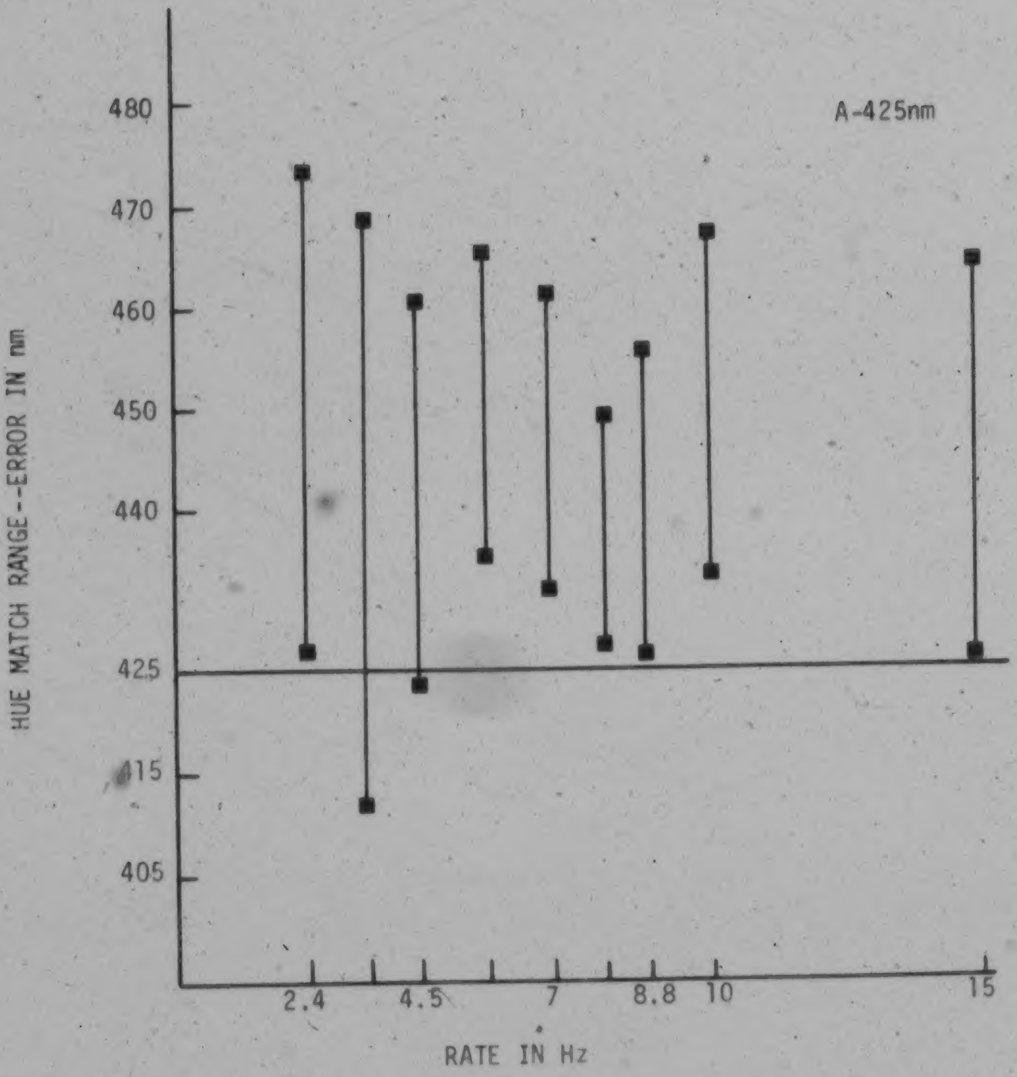

Figure 19-A. Deutan hue match ranges as a function of rate of intermittency.

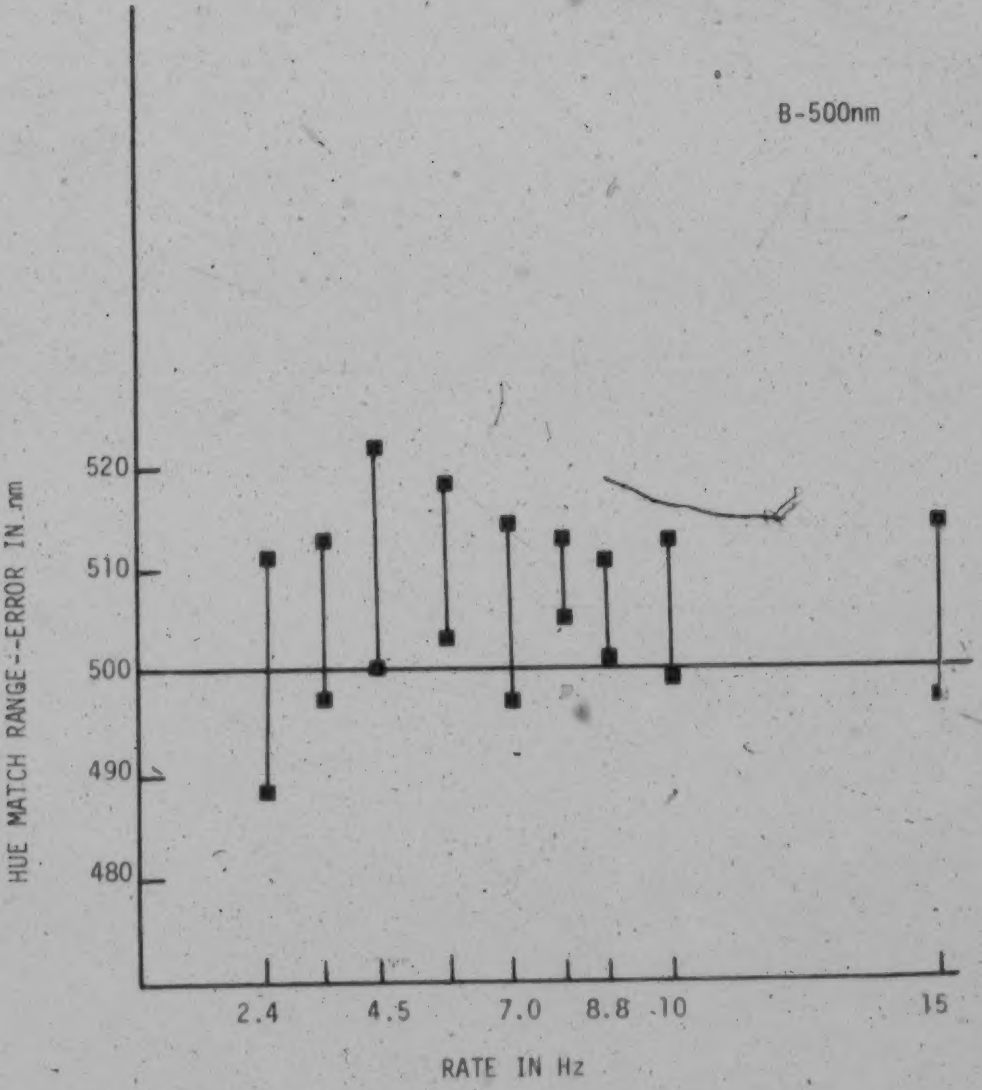

Figure 19-B. Deutan hue match range as a function of rate of intermittency.

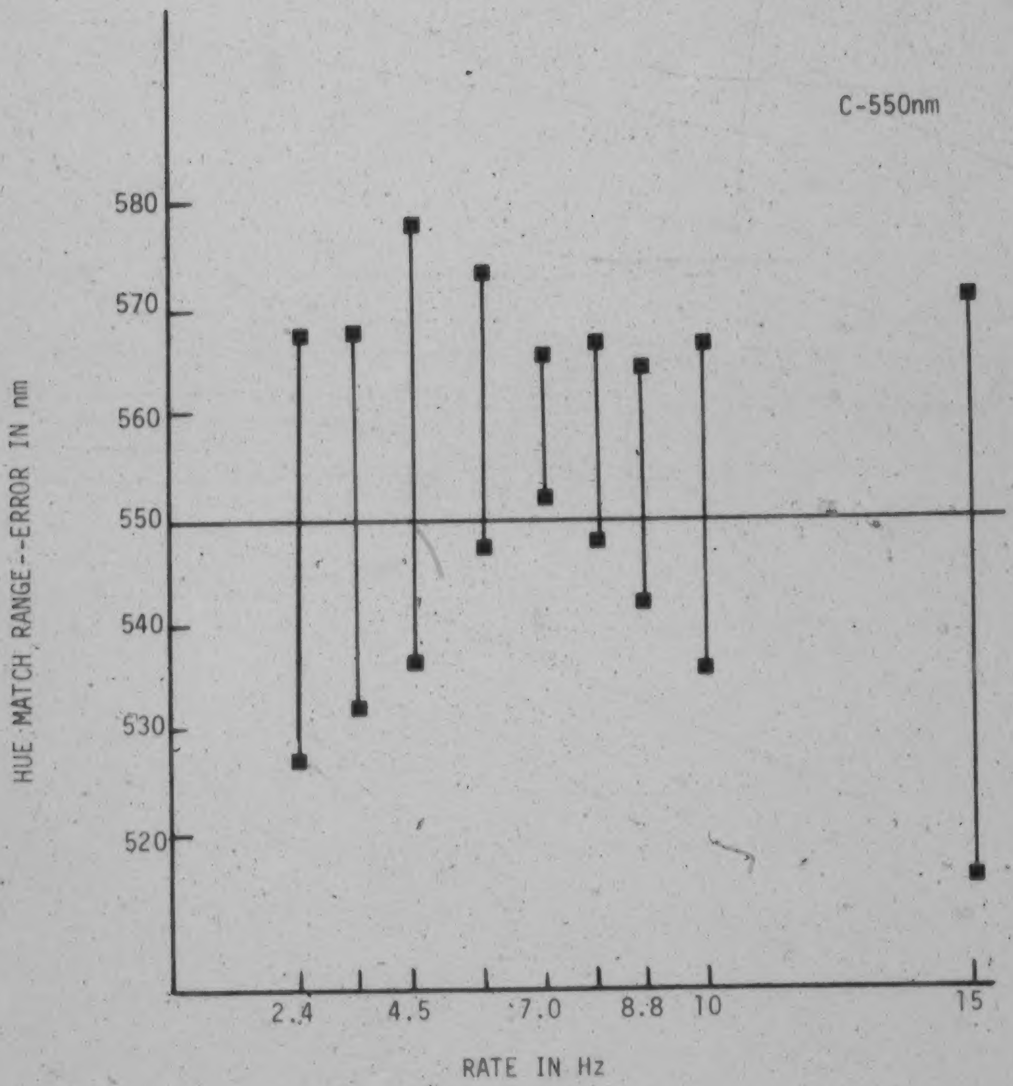

Figure 19-C. Deutan hue match ranges as a function of rate of intermittency.

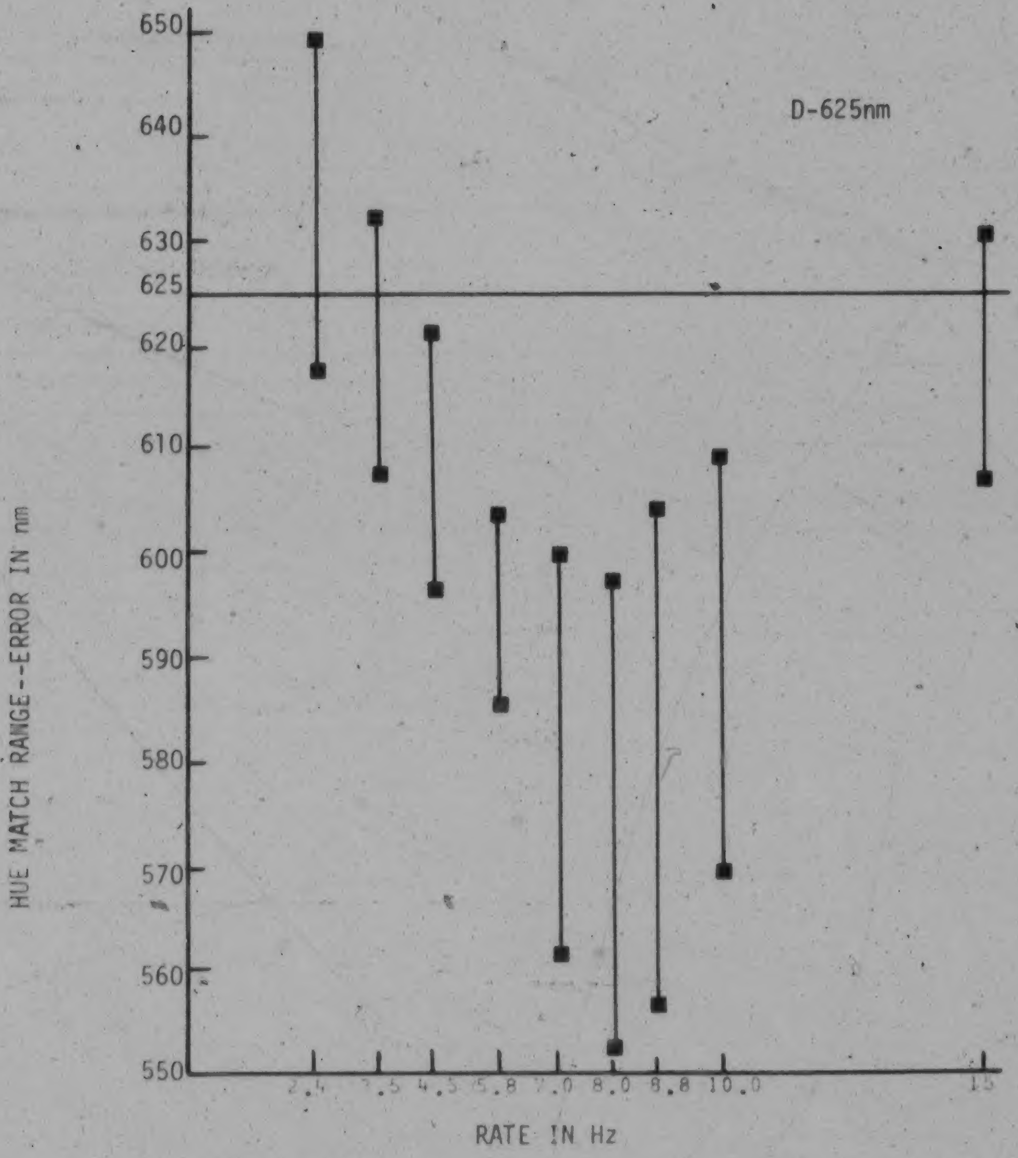

Figure 19-D. Deutan hue match ranges as a function of rate of intermittency.

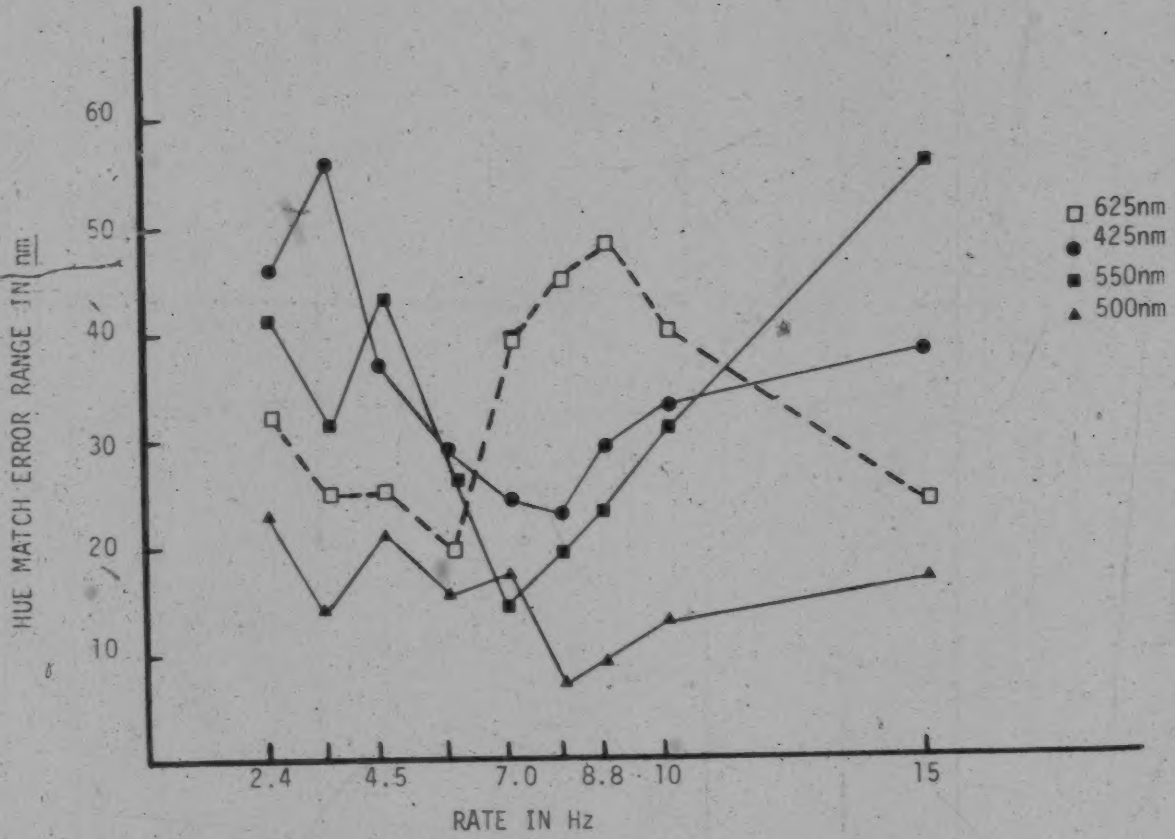

Figure 20. Deutan hue match errors as a function of rate of intermittency (TT curves).

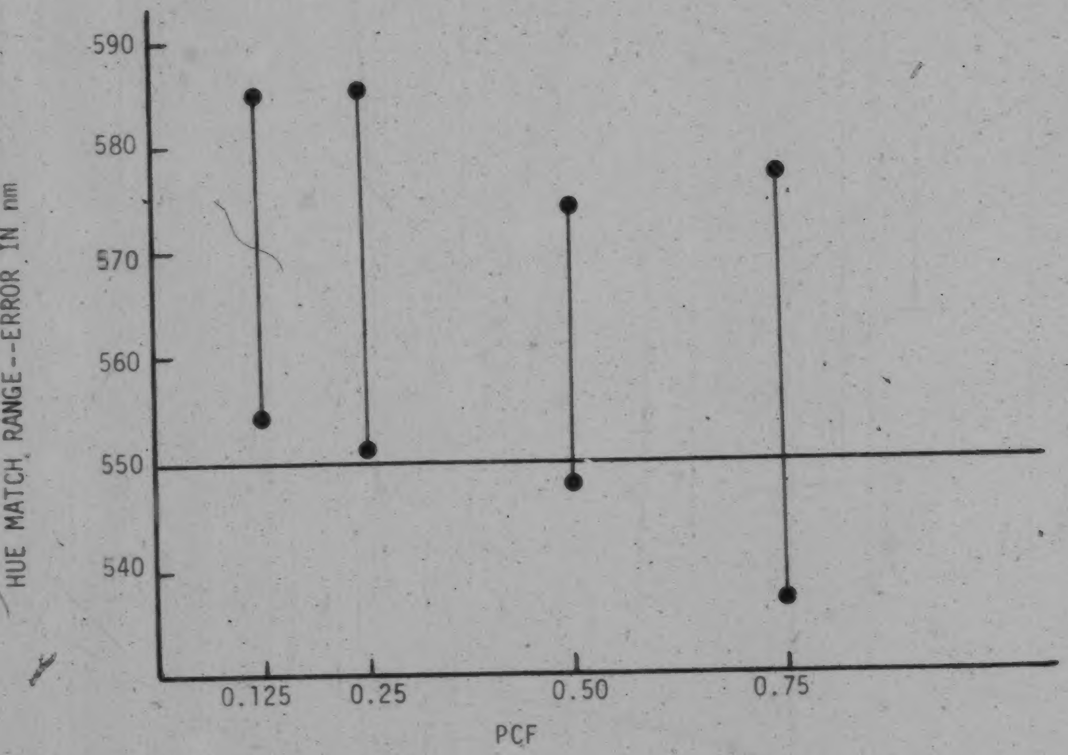

Figure 21. Deutan hue match errors as a function of PCF (550nm, 5.8 Hz).

wavelength dependent and follows the trichromatic curve only at 550nm. For the other three spectral areas, brightness increases to steady state near 15 Hz, which indicates that BE may occur here at higher luminosity levels.

III. Saturation Studies

Saturation as a function of rate of intermittency for GT is represented in figure 23. Like brightness, saturation is wavelength dependent with only 625nm resembling the trichromatic function. 425 and 550nm show an SS effect at midrange rates (8-18 Hz) and 500nm showed little change in either direction. Figure 24 shows saturation over PCF for 3 rates. At 3 Hz and fusion deutan curves generally follow trichromatic expectations. At 10 Hz, however, saturation over PCF is wavelength dependent with 625nm resembling the trichromatic function; and 424 and 550nm being more or less opposite. This suggests the same type of supersaturation mechanism which operates at 3 Hz.

Figure 25 shows DES as a function of wavelength. This function resembles that of a trichromat except near 500nm where GT reported little or no desaturation. There also seems to be an inverse relationship between DES and hue matching ability in GT's data. (Compare shapes of rate curves above 5 Hz for each wavelength in figs. 20 and 23).

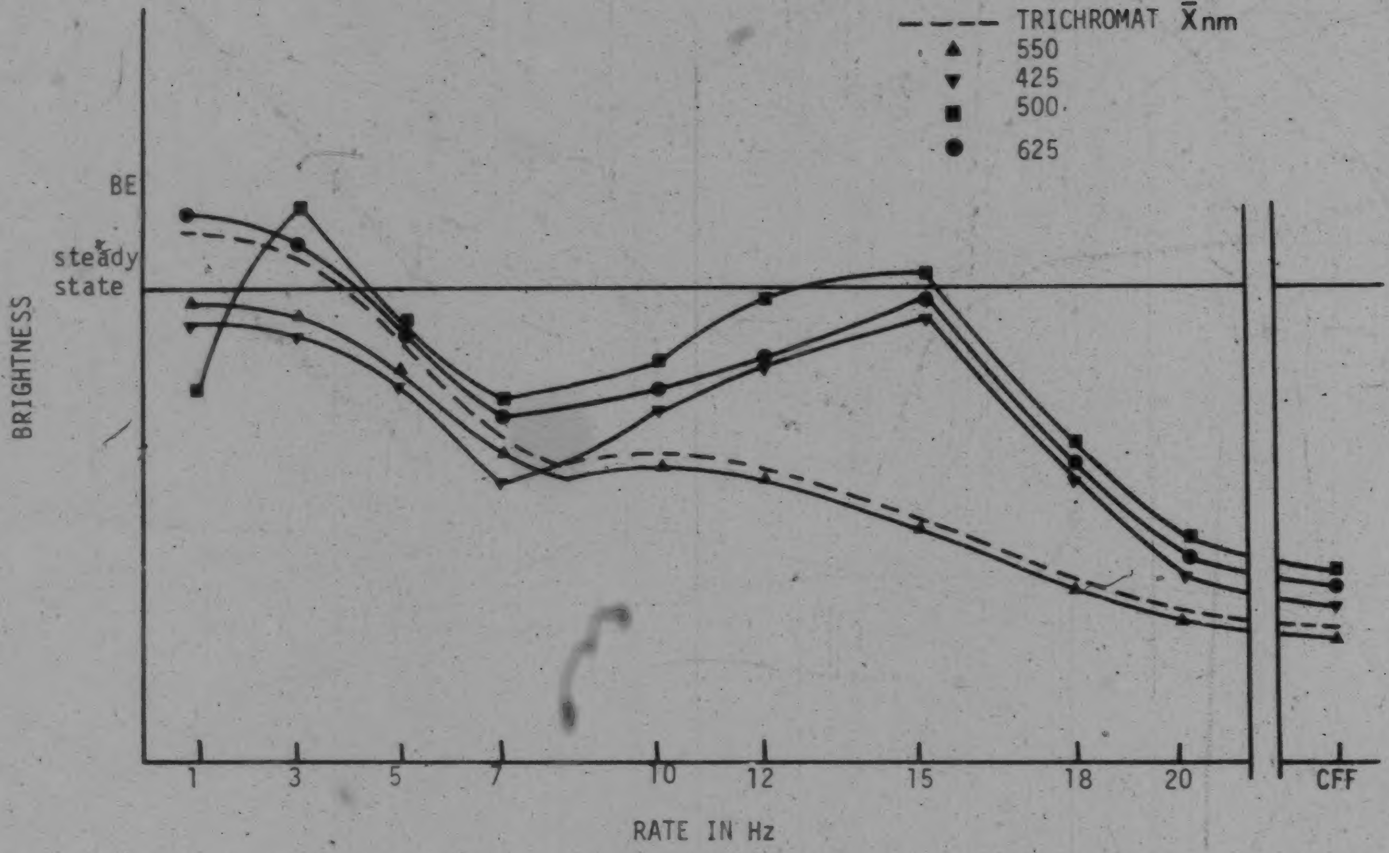

Figure 22. Deutan brightness as a function of rate in four spectral areas.

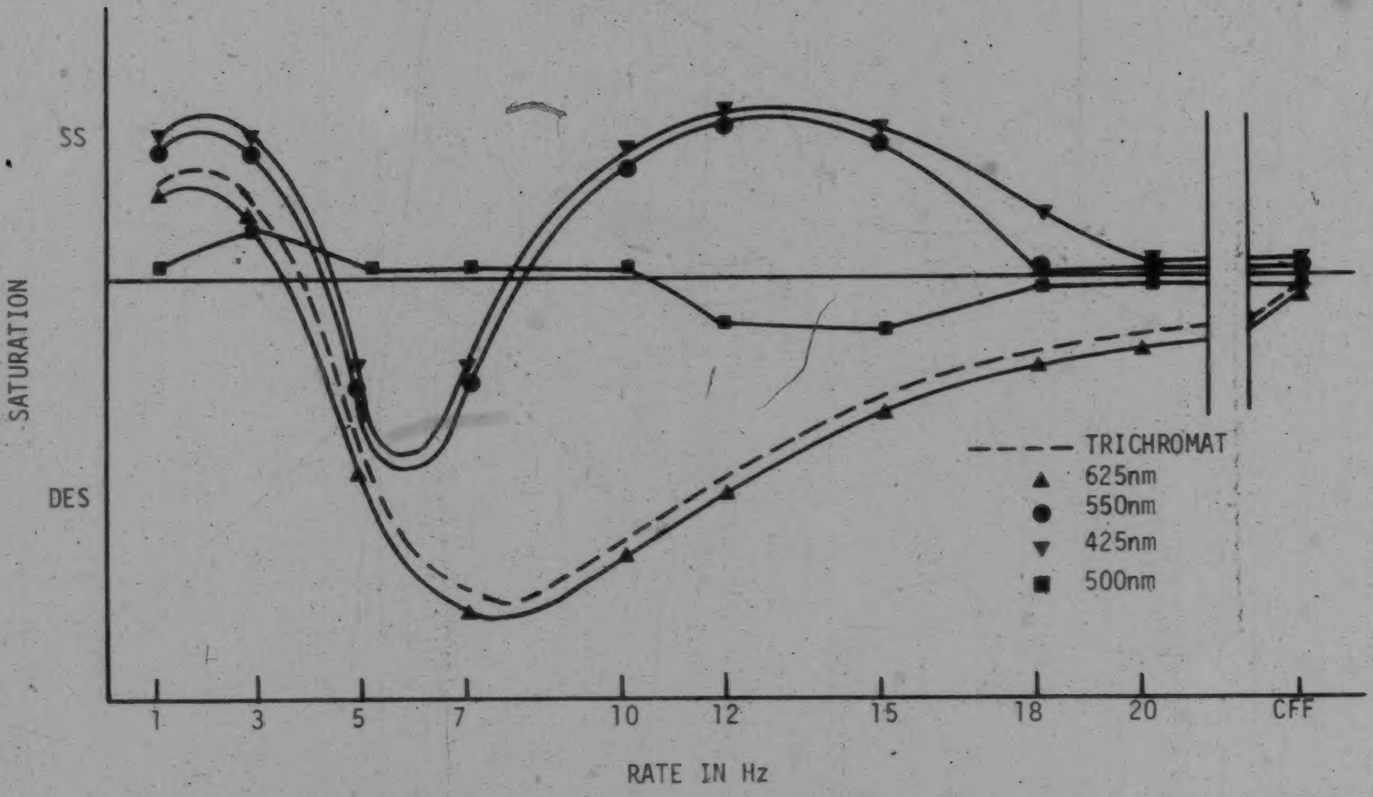

Figure 23. Deutan saturation as a function of rate.

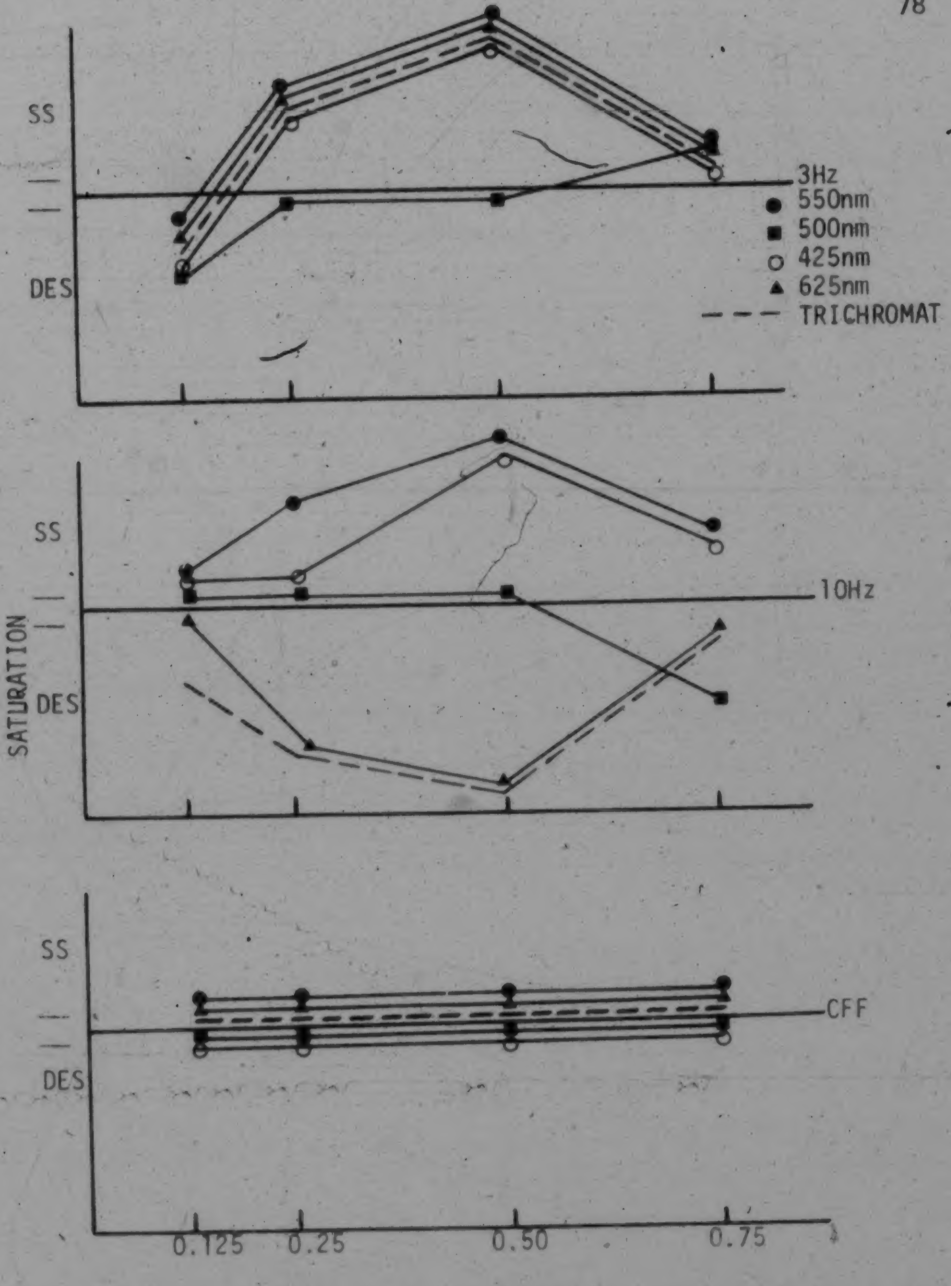

Figure 24. Deutan saturation as a function of PCF for 3Hz, 10Hz, and CFF.

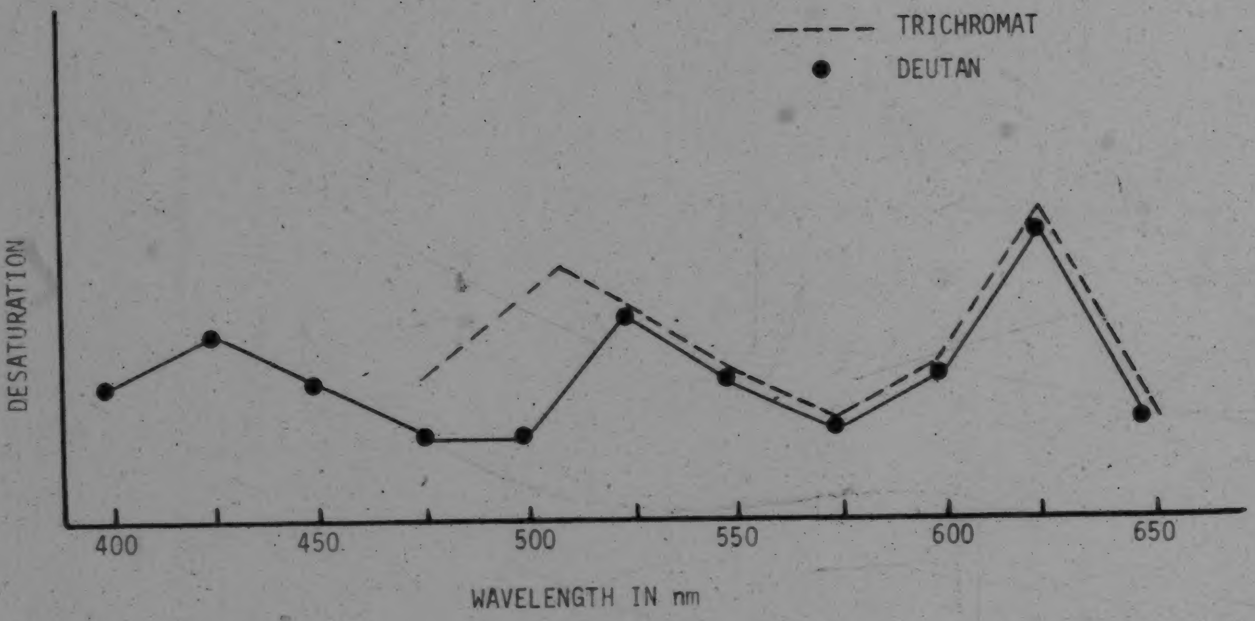

Figure 25. Deutan desaturation as a function of wavelength at 7Hz, 0.50 PCF.

DISCUSSION

The major findings fall into two classes for purposes of interpretation:

(1) evidence for temporal tuning (TT) mechanisms in the visual system, and

(2) evidence for a neurological relationship between hue and saturation.

MacDonald (1971) proposed a model to account for basic changes in hue and saturation under photic intermittency. This model has since been elaborated to include TT mechanisms. It involves a temporal color space which incorporates flicker changes and ordinary color mixing processes within the same conceptual framework. The model is presented here along with supporting experimental evidence.

THE TEMPORAL TUNING MODEL

The model works equally well for both three and four color systems (or for any number of colors), but let us assume for demonstration purposes that there are 3 physiological primaries: red, yellow, and blue. Each of these colors occupies a pivotal position on any modern color-mixing triangle, for example, the C.I.E. model (fig. 26). Within this triangle can be found all the hues and saturations which arise as the result of combinations of the basic three. Desaturated hues and whites are situated towards the centre.

Apart from this color mixing process, the author suggests that each primary system has a range of temporal possibilities within which it can effectively process color information. These ranges arise as the result of interactions between conduction and recovery times in underlying sequences of biochemical reactions. The reactions take certain amounts of time to go to completion. These times vary between systems and between channels within each system. The variation between channels within any system provides the temporal range for that particular system.

The magnitude or width of these ranges varies for each of the three systems, with yellow being the narrowest (evidence for this is presented later). The range width may reflect the degree of evolutionary specialization for each color system.

Within each system, the magnitude of response for production of neural color information is optimal at, and distributed about, some point in the midrange, defined

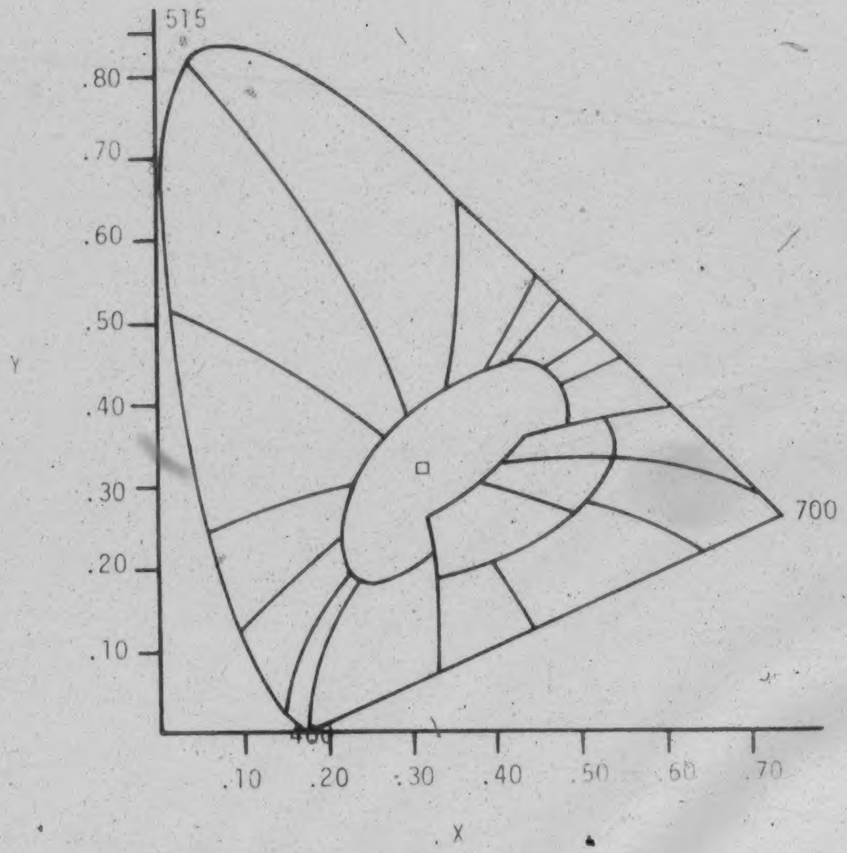

Figure 26. The CIE chromaticity diagram.

here as the locus of temporal tuning (fig. 27). this locus represents the set of temporal (or biological) circumstances under which the visual system interprets and processes input as if it were continuous rather than discrete. The range for any color can also be thought of as a range of synchrony of discharge where the discharge-recovery ratio is positively skewed on one side of the TT locus and negatively skewed on the other side. For any color system, the distribution of discharge-recovery ratios provides a distribution of interactive possibilities between that system and the other primary color systems. The result is a variation in purity or saturation on a temporal dimension, for each color system.

THE TEMPORAL COLOR DIAGRAM

To illustrate the mechanism of interaction, let us further suppose that the three color ranges are juxtaposed such that they interact totally at one end of the temporal continuum, and are completely separate at the other. The interactions between systems are analogous to any of the various color mixing models wherein, desaturated hues arise as the result of the mix. This relationship between the three systems can be conveniently described in the form of a pyramidal shape (fig. 28) where the sides or faces represent the TT

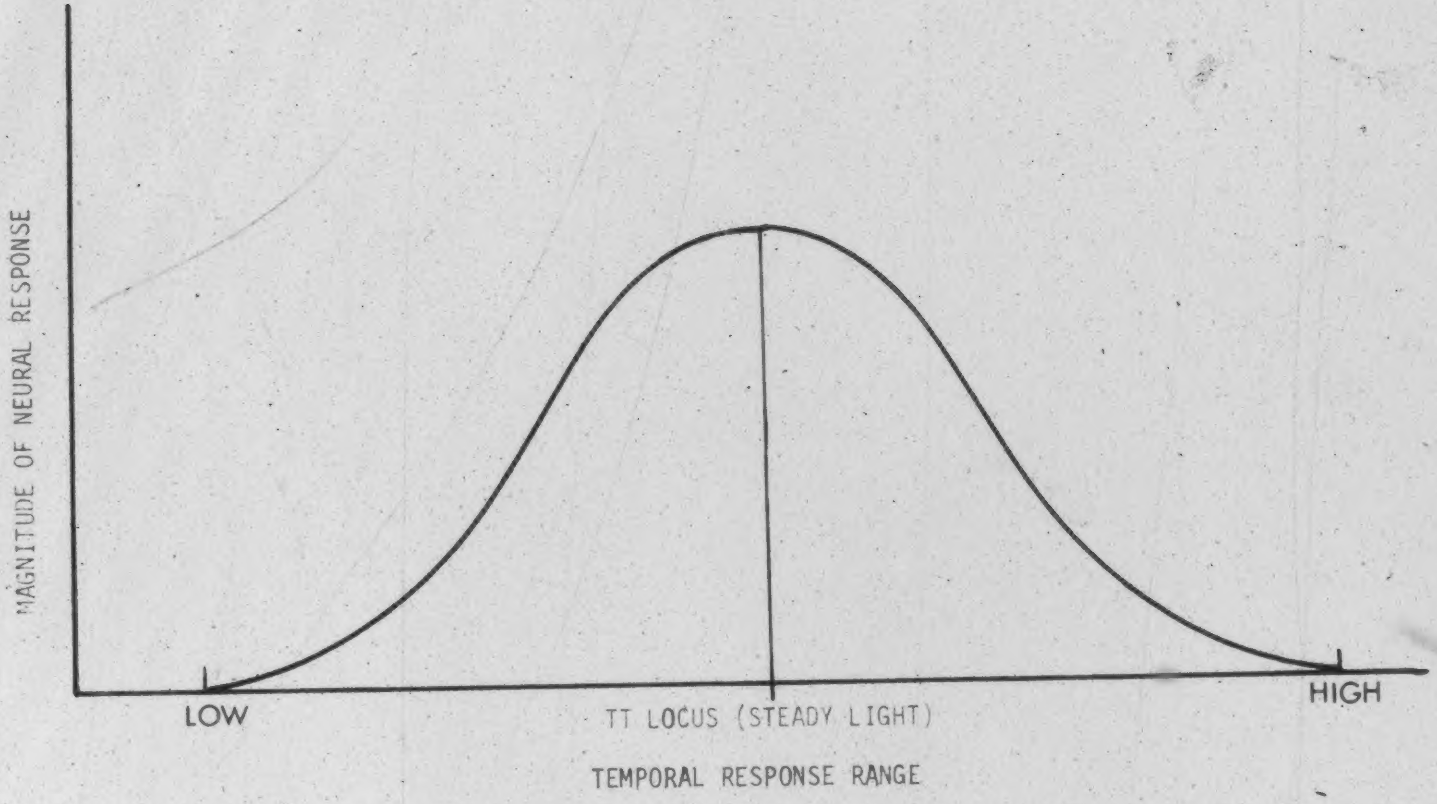

Figure 27. Temporal range and distribution of neural response for a primary color system. The temporal response dimension refers to a range of recovery/discharge ratios from single pulse conditions at the low end to intermittency conditions at the high end.

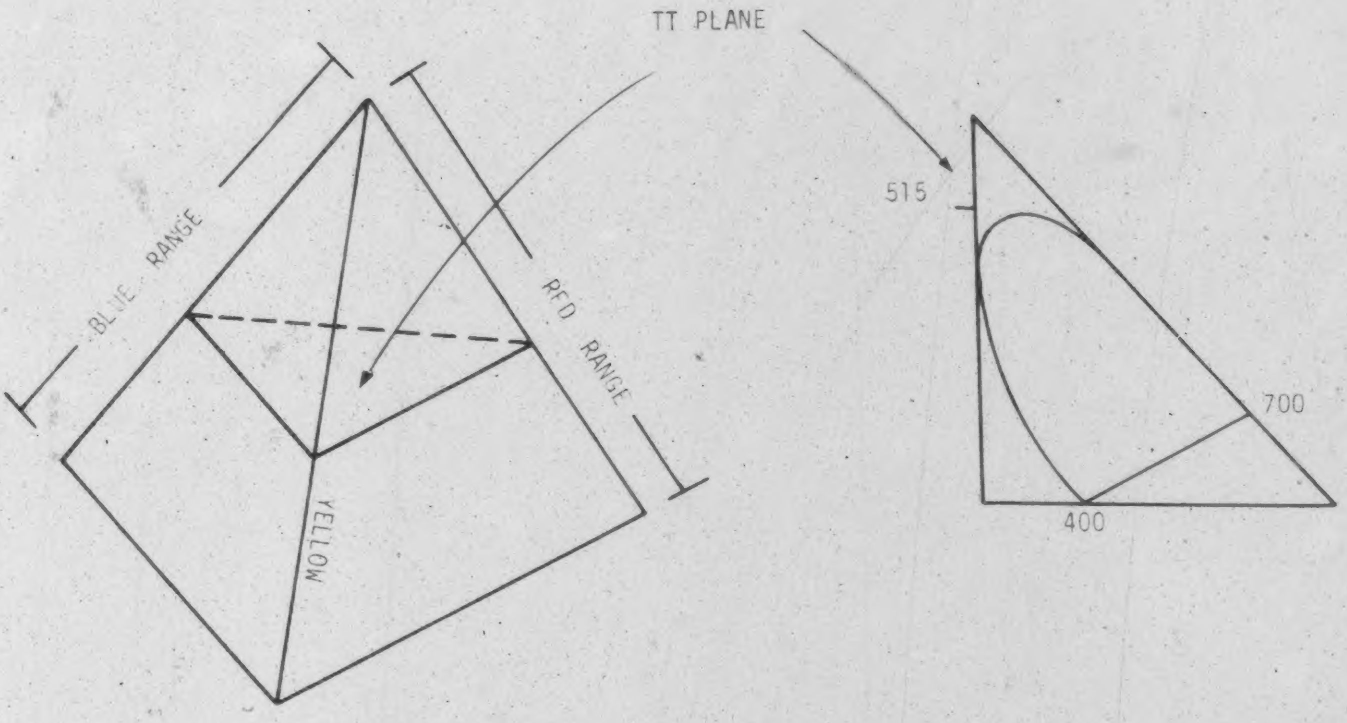

Figure 28. The MacDonald temporal color diagram. TT ranges for the 3 primary colors lie on the oblique vertical dimensions. Various 2-dimensional color mixing planes, such as the CIE, lie in the horizontal dimension.

ranges of the primary colors. In this conceptualization, time factors lie on the vertical dimension. Midway up the time ranges lies the plane of temporal tuning which in plan view is a triangle with the primaries lying at its vertices. Color mixing or color integration relationships lie in horizontal planes, but only one of these planes, the TT plane, represents a color diagram (such as the CIE) in static time (that is, under continuous illumination).

Within the model then, saturation is redefined as a function of time; that is, as the neurological potential of any system to produce color information independently of, or in relation to, the other color systems. Temporal parameters underlie the mechanisms through which the three systems are neurally related in the production of color information.

The model also posits that desaturation is not basically different from whiteness or from any reduction in saturation within static time. Both effects occur as the result of the same sort of integrative or mixing procedures, but the temporal patterning is different for each. This similarity of process can be illustrated by considering two of the three color ranges in pyramidal arrangement (fig. 29).

The intersection of TT loci (A in fig. 29) for red, yellow, and blue, forms the plane for color mixing in

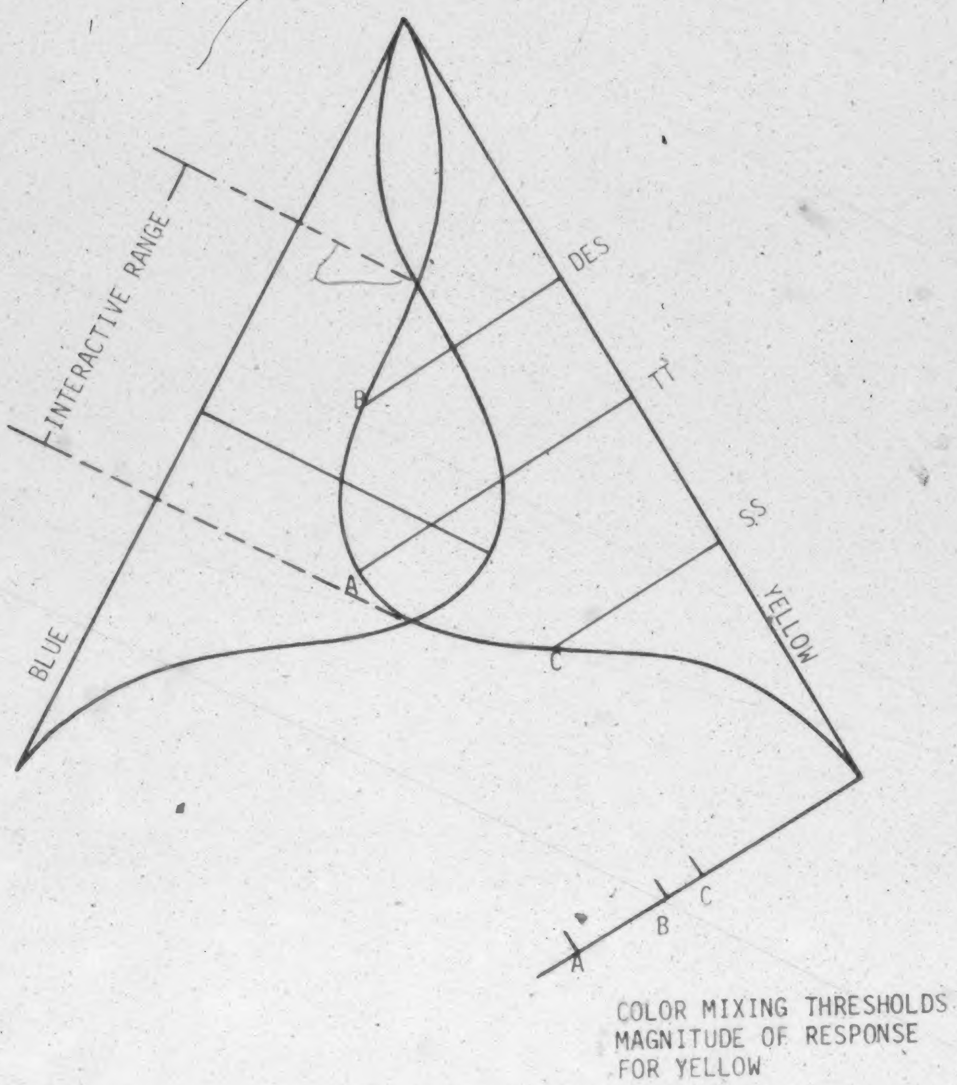

Figure 29. Section of temporal color pyramid showing color mixing, DES, and SS planes.

static time. The intersection of other temporal loci in the interactive range (e.g., at B) forms the planes for color mixing through hue shift and desaturation under photic intermittency. The existence of color producing loci outside the interactive range (e.g., at C) is the basis for supersaturation or production of color information in any one system independently of the others. It is important to note that the response thresholds for these three classes of color purity are different. They also should change, according to the shape of the curve, with changes in the conditions of photic intermittency.

An explanation for direction and magnitude of hue shift is presented later.

Luminosity is introduced as an inverse function of the area of any horizontal plane in the pyramid, where color systems either interact, or are separate. The inverse area function is accounted for by a neural recruitment model which is outlined here, and developed later to explain the relationship between HS and DES.

Each color system, channels, cones, or whatever, has a spectral range over which it can process photic information. MacNichol (1964), Rushton (1962) and others have shown that for specific cones, spectral absorption ranges are broad enough that the three systems overlap considerably (fig. 30).

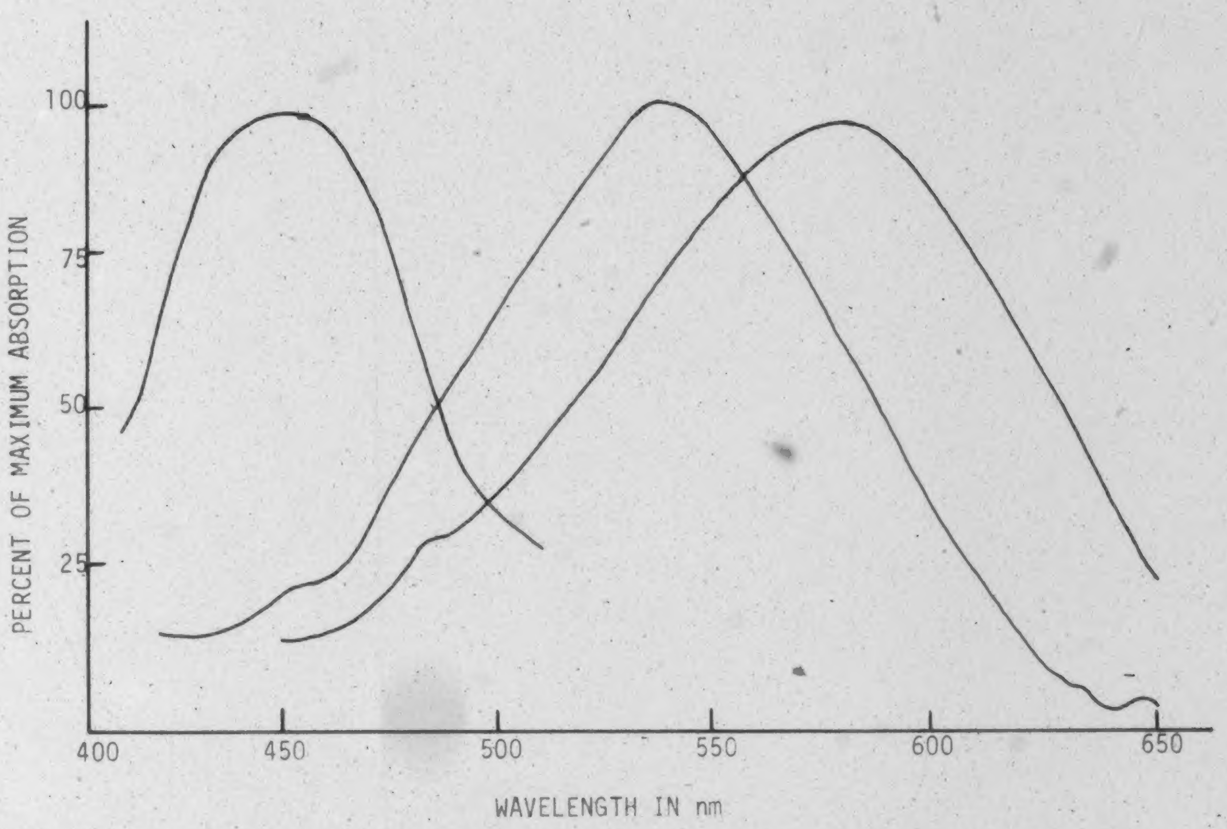

Figure 30. Spectral-sensitivity curves for three cone pigments (Macnichol, 1964).

When a certain waveband and intensity of photic stimulation impinges upon the receptors, it recruits neurological potential for color processing from each of the three systems, in proportion to its intensity and spectral distance from each. As intensity is increased, neurological potential is recruited from each color system, but proportionally more is recruited from the spectrally closest system than from the other two. When intensity is raised near the threshold where all or most of the potential in the closest system is recruited, it begins to recruit proportionally more from the spectrally more distant systems. When this happens, the level of neural interaction between the color systems increases, and the Bezold-Brücke shifts occur.

Since the response capacity (amplitude of curve in fig. 27) for any color system is fixed by the biological limitations of its sub-systems (e.g., cones, etc.) this shift in recruitment ratio can be represented in the temporal color space only in the form of a "collapse" system where the base, face, or threshold level of the more luminous color system is moved geometrically closer to the other two (fig. 31). This is difficult to conceptualize as it involves representing a positive energistic change in terms of a negative change in space. The result is a decrease in the area of the horizontal TT plane in inverse proportion to the increase in

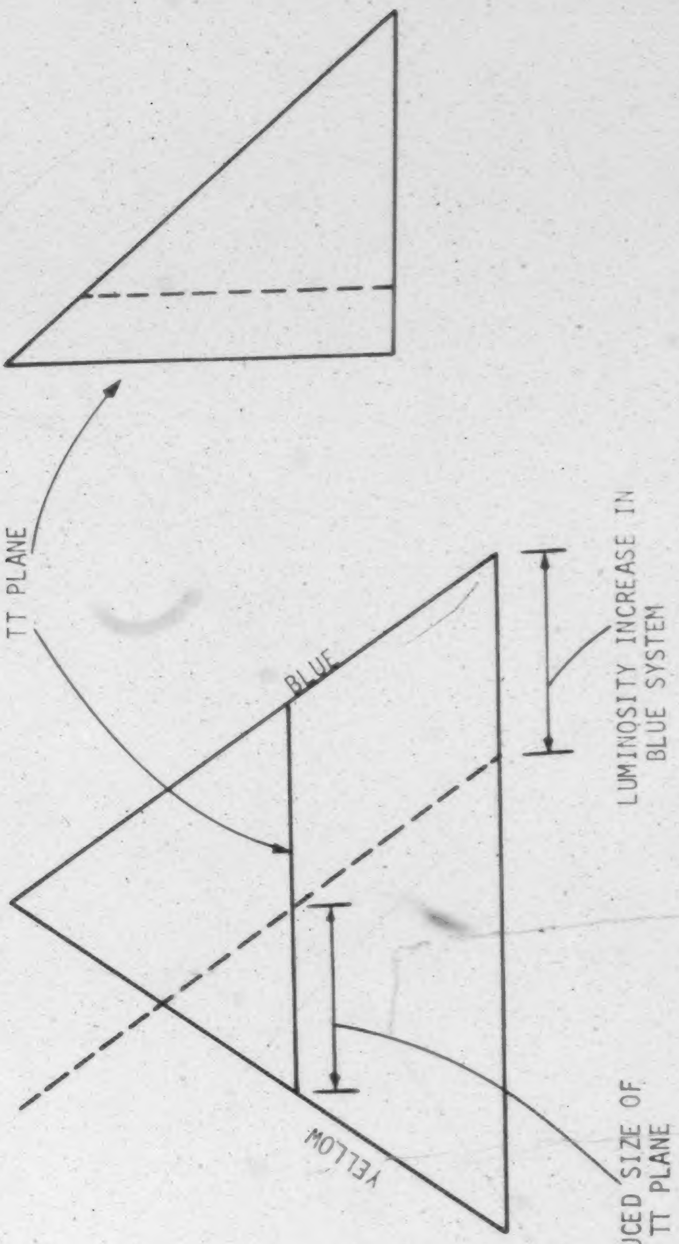

Figure 31. Pyramidal collapse system for increase in luminosity

luminosity. The increase in neural interaction which occurs with higher luminosity, is represented in the increased overlap area or interactive range within the color mixing triangle. This increase in interactive range is demonstrated here in a vertical plane (fig. 32) but can be shown in the horizontal (TT) plane as well.

Both Hue shift under intermittency and the Bezold-Brücke changes, under steady illumination, are explained later in terms of this luminosity dependent change in neural interaction.

Major experimental findings are presented here in support of the temporal tuning model.

EXPERIMENTAL EVIDENCE FOR TEMPORAL TUNING

Within the present study, evidence for temporal tuning is found in both luminosity and chromaticity results.

In the luminosity results, the monotonic relationship between the wavelength functions for luminosity, BE, and BE threshold (figs. 4, 5, and 12) suggests that BE is exponentially related to luminosity. Such a relationship implicates a TT mechanism for brightness perhaps in the form of a variation of Weber's law which operates on a time basis. Changes of BE with luminosity may also reflect a Weber fraction which

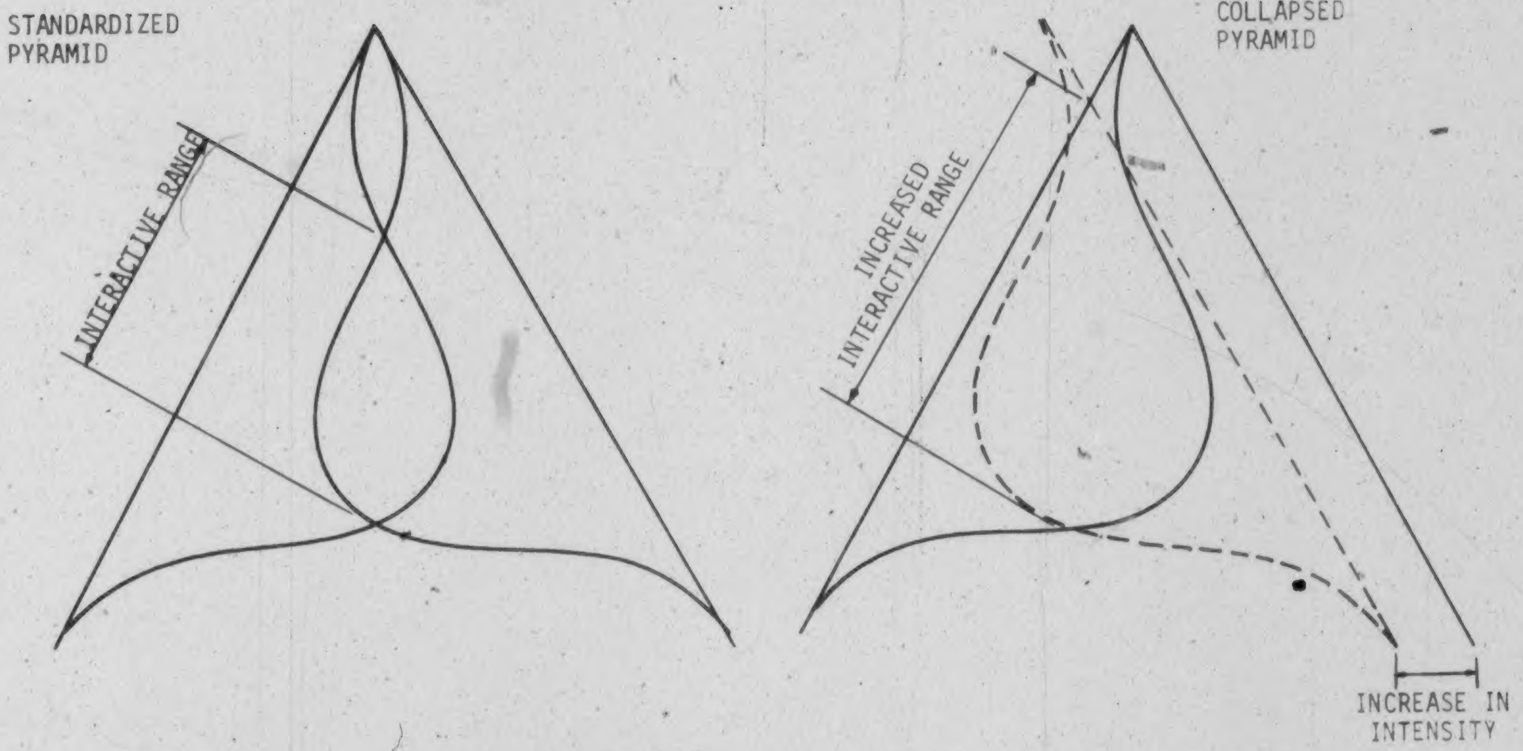

Figure 32. The effect of increased luminosity on color interaction in the collapse model.

operates in static time.

In the chromaticity system evidence for a TT is found in the symmetrical operation of changes in hue and saturation about certain conditions of intermittency.

The existence of SS (fig. 13) and its symmetrical operation with DES for PCF (fig. 14) and for threshold over wavelength (fig. 5) suggest a single bi-directional process for saturation, which yields neural information for any particular color in varying magnitudes depending upon the conditions of temporal patterning.

Hue shift and matching data also support the notion of a single bi-directional process for color production. Direction of HS is, to a certain extent, dependent upon rate and PCF (fig. 6, Ball and Bartley, 1965, 1968).

The deutan hue matching evidence is especially strong. In figures 19 and 20 hue match error envelopes and TT curves are plotted for several wavelengths as a function of intermittency. The hue match envelopes (fig. 19, B and D) show the range of errors to be positive (i.e., greater in nm than the match target) at some rates of intermittency, and negative at others. The TT curves (fig. 20) show that magnitude of hue match error for deutan varies with rate and wavelength; and is better under certain conditions of intermittency than under steady light for some wavelengths. This wavelength variation is evident in a similarity in TT function for those wavelengths which were most poorly matched under steady illumination (425 and 550nm) and a difference in TT function between these two and 625nm which was better matched under steady illumination (fig. 20).

Wavelength variation is also evident in a comparison of figures 16 and 17 where hue match under 10 Hz improves in some spectral areas, but worsens in others.

Deutan results showed further evidence of wavelength specific TT effects in saturation as a function of rate (fig. 23); brightness as a function of rate (fig. 22); and saturation as a function of PCF (fig. 24) where some wavelengths follow trichromatic expectations, and others do not.

These data support earlier notions of temporal processing similarities between trichromats and dichromats (Ball and Bartley, 1968). They also provide good evidence for the idea firstly that TT loci are different for deutans and trichromats; and secondly that under intermittency, the loci of maximum effective processing shift within the ranges. The latter idea is especially supported by the TT curves and by a comparison of saturation over rate for deutan and trichromats (figs. 13 and 23).

Trichromats showed further evidence of wavelength specific TT effects in SS decay times for single pulses (fig. 16).

Evidence for the notion that yellow has a more narrow range of effective temporal processing than the other color systems is found in the bi-modal shape of the saturation threshold curves (fig. 5) and in the similar shape of the curves for magnitude of DES over wavelength (figs. 15 and 25) which both show minima near 575nm.

The explanation for this is that yellow cannot desaturate as much as blue or red under intermittency because it is already close to its maximum desaturation capability under steady illumination. That is, yellow has a short temporal range of effective color processing, and consequently, the yellow discharge-recovery ratio varies less from its TT locus to the interactive end of its range than do the corresponding ratios for red and blue. The yellow TT locus is closer, in an absolute sense, to the interactive end of its range, than are the corresponding loci for red and blue.

The magnitude of neural response for each primary system may, in some way, be related to the range width for that particular system, since the luminosity thresholds for saturation changes are lower for 575nm than for other wavelengths. The monotonic relationship between these curves (figs. 5 and 15) suggests a Weber type of function similar to the one suggested for BE.

This evidence concludes the present argument for temporal tuning. Minor changes in the temporal color diagram are now suggested.

FORM CHANGES IN THE TEMPORAL COLOR PYRAMID

The pyramidal shape of the color diagram is only theoretically regular. It serves much the same purpose as the geometrically regular triangle which encompasses the CIE color diagram. Several changes in the form of the MacDonald color pyramid (fig. 28) are suggested in the light of the experimental findings, and in other implicit assumptions.

1. The shape of the horizontal plane at the TT locus should be adjusted to CIE specifications.
2. The base and apex of the pyramid are false and should follow the contours formed by the neural production functions of the TT ranges.
3. The yellow face of the pyramid should be shorter than the others to account for the narrower yellow TT range.
4. Above the TT plane, both blue and red faces should be collapsed on the horizontal plane toward the yellow face to account for HS.

These adjustments complete the description of the color diagram. Evidence for interaction between HS and

DES, and a model accounting for this evidence is presented in the next section.

EXPERIMENTAL EVIDENCE FOR A NEUROLOGICAL RELATIONSHIP BETWEEN HUE SHIFT AND DESATURATION

One of the main hypotheses of the thesis was confirmed in the study of relative magnitudes of HS and DES. A comparison of figures 8 and 9 with figure 15 shows that the magnitudes of HS and DES are reciprocally related on both sides of 575nm.

According to the TT model, 575nm (the yellow primary) may, under steady illumination, be nearer its point of maximum DES than blue or red since it has a shorter temporal range. Intermittency conditions optimal for DES may yield only small changes at this spectral point.

Deutan results strongly support the hypothesis of a relationship between HS and DES. When TT curves (fig. 20) are compared with saturation over rate (fig. 23), the magnitude of hue match error appears to be inversely proportional to the magnitude of DES for each of four wavelengths: 625, 550, 500, and 425nm. Conversely, DES and hue curves do not appear to be similar to brightness curves under similar conditions of intermittency. There are several examples of this:

(A) Phenomenal threshold curves (fig. 5) where the BE functions differ from chromaticity functions;

(B) Magnitude of HS and saturation which are bi-modal over wavelength compared with BE which is not (figs. 9, 12, and 15);

(C) Magnitude of brightness over rate as compared with magnitude of saturation for trichromats (figs. 10 and 13); and HS and DES for the deutan (figs. 20, 22, and 23).

(D) Magnitude of brightness compared with that of HS and saturation over PCF in trichromats (figs. 11 and 14) which show different functions.

EXPLANATION FOR THE RELATIONSHIP BETWEEN HUE SHIFT AND DESATURATION

A two-stage model is presented here to account for the relationship between HS and DES. The first stage involves an harmonic model of DES and HS based on differences in neural processing times for various colors.

(A) A TEMPORAL-HARMONIC ACCOUNT OF HUE SHIFT AND

DESATURATION

It was earlier suggested that TT ranges varies for the three primary colors as a function of the temporal interaction between discharge and recovery times of the underlying biochemical reactions. There is a history of evidence that certain colors are processed more quickly by the visual system than others. This evidence is of direct importance to the TT model.

König (1897) concluded that information from longer wavelengths is conducted by fibers which synapse only with cones, whereas information from the short end of the spectrum is carried by channels which synapse with both rods and and cones. Walraven (1966) and others later adapted these ideas into color information processing models. Chang (1950) demonstrated that the visual system codes red information more quickly than blue. Brindley (1965) suggested that the blue cone mechanism has a lower CFF than red or green mechanisms. Madsen and Lennox (1955) showed that for cats, various types of spectral pass-bands evoked different types of activity at the visual cortex. Dustman and Beck (1963) later reported that the waveform of the visual evoked potential (VEP) in adult humans is both wavelength specific and consistent over time within subjects (although not between subjects).

Shipley, Jones, and Fry (1966, 1968), investigated VEP waveforms for different colors more precisely. They noted that latter parts of the waves (300-500ms) had the same form for all colors, however wavelength specific differences existed in the early parts of the waves. Implicit times (ITs: the time from the onset of the stimulus to the peak of the response) were longer for violet and green than for red and yellow (See Table below).

IMPLICIT TIMES FOR FOUR WAVELENGTHS
(from Shipley, Jones, and Fry, 1968)

COLOR	WAVELENGTH	TIME
Red	680nm	180ms
Yellow	575nm	200ms
Green	520nm	300ms
Violet	430nm	250ms

Waveforms from the short end of the spectrum showed large negative potentials preceding the implicit times whereas those from the long end did not (fig. 33).

These findings and others by Nilsson and Nelson (1971) suggest that color coding is represented in the

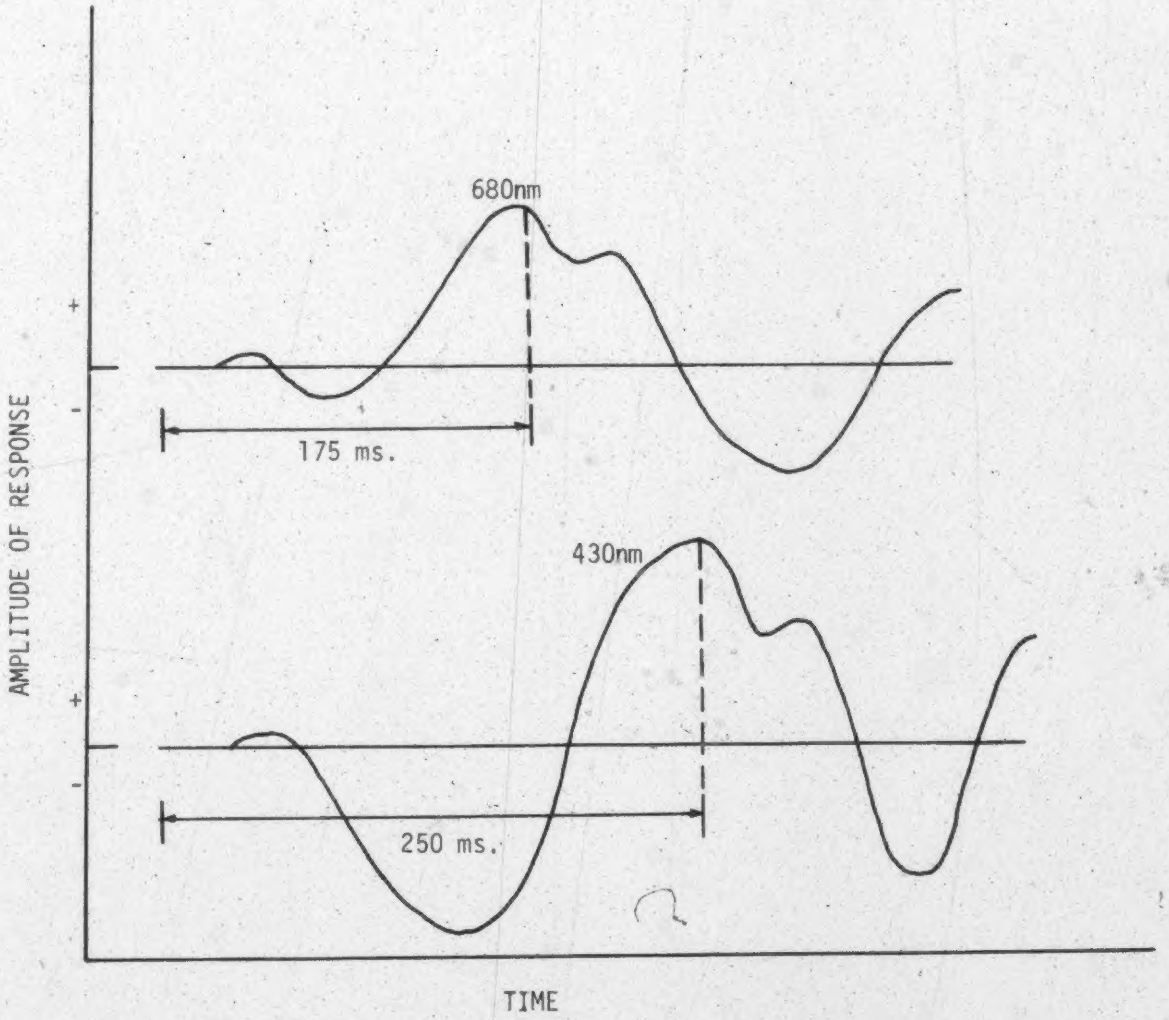

Figure 33. VEP waveforms for two wavelengths.

early components of the wave.

If a color is coded before the implicit time, or before some other specifiable time early in the wave, then both HS and DES can be explained within the same conceptual framework.

Let us assume for demonstration purposes that the implicit time in the VEP for any color represents that point in time when the biochemical processes for that color have gone to completion. Under photic intermittency of 5 Hz (i.e., 200ms cycles) neural information for 680nm and 575nm could be fully processed within the duration of each cycle since the ITs for these wavelengths are not longer than the cycle length. Their hue characteristics under steady illumination could be maintained over a train of pulses, given the appropriate conditions of intermittency (fig. 34). Violet and green information however, could not be fully coded within the duration of one cycle. In a sequence of pulses, disruptions in temporal patterning of the information for these colors would begin with the onset of the second pulse in the train. For example, in the green system information from only the quicker conducting channels could be coded prior to the onset of the second cycle. After several cycles, residual information from preceding cycles would be summated or integrated with information from succeeding cycles through non-completion of the

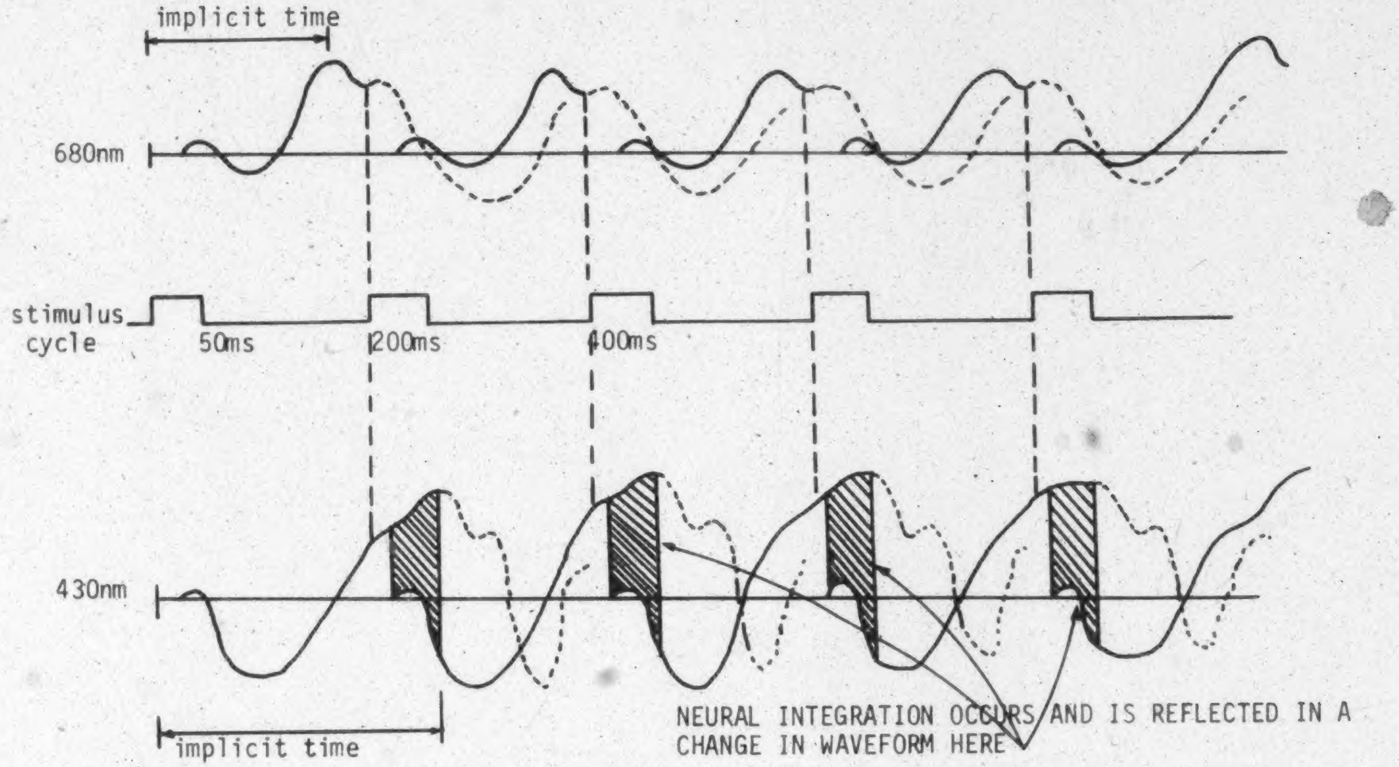
implicit time
680nm
stimulus cycle
50ms
200ms
400ms
430nm
implicit time
NEURAL INTEGRATION OCCURS AND IS REFLECTED IN A CHANGE IN WAVEFORM HERE

Figure 34. Cyclic effects on VEP waveform for two wavelengths.

biochemical processes within each 200ms cycle. the harmonic result would be the production of neural information for hues other than the steady stimulus hue. These hues would then summate to produce either HS, DES, or both. The change in the perceptual end result would be reflected in a change in waveform of the VEP (fig. 34).

The magnitude of this phenomenal color change depends upon the magnitude of the extraneous information produced, but the dimensional form of the change, (whether hue shift, desaturation, or both) depends upon the spectral distribtuion of this information.

If the information is distributed symmetrically about the steady stimulus hue, or about some other balance point in any Newtonian-based color-mixing scheme, then, in accordance with the spectral relationship between balance point and hue, the extraneous neural information should summate to produce whiteness and the resultant hue will be desaturated. If the information is distributed asymmetrically, or in skewed fashion, about the balance point, then the resultant of the summation will differ in hue from the steady state stimulus. Desaturation will occur but hue shift will also occur. The magnitude of DES and HS will be reciprocal, the total product being limited by the amount of extraneous neural information produced (algebraically, HS x DES = K). The magnitude of each will be a function of the skewness of the distribution of extraneous neural information.

(B) A SPECULATIVE NEURAL RECRUITMENT MODEL FOR HUE SHIFT AND DESATURATION

The mechanism for relating hue shift and desaturation may involve the model of recruitment of neural information which was previously suggested to explain luminosity increases. At the receptor level this model may be evolved from the overlapping portions of photopic absorption curves (fig. 30) but, for the present state of development of this model, it is conceptually better to consider three more general color systems, each having a range of spectral possibilities for the production of neural information, which can operate at any specific place, or at all places, in the visual system. It is important to note that, like the pyramid, this model can work equally well for three, four, or any number of primary colors.

For demonstration purposes, let us assume that the distributions for recruitment of neural response overlap and are symmetrically distributed about certain spectral points (fig. 35), although not necessarily about the peak absorption wavelengths for the cones (fig. 30). The degree of overlap is a function of the temporal

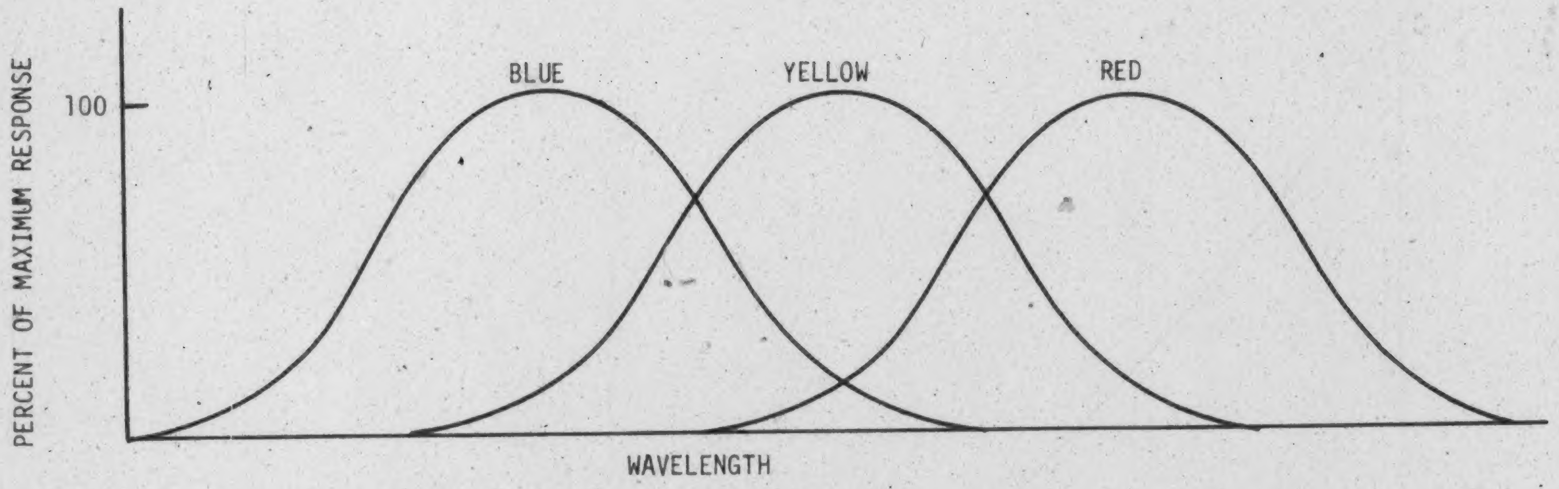

Figure 35. Spectral distribution of recruitment of neural response for three primary color systems.

conditions.

The diagram then, represents the potential for any of the three systems to be recruited as a function of wavelength and intermittency. Within each system, subsystems are activated as a function of luminosity in much the same way that cone discharge thresholds vary with luminosity (fig. 36).

SPECULATIVE EXPLANATION FOR DESATURATION

Let us assume for demonstration purposes that the points of intersection of the three curves are the spectral points of no hue shift (A, B, and C, fig. 37). If we present a stimulus of known and low intensity at one of these (e.g., at A, 515nm), the types of channels or subsystems it recruits will be symmetrically distributed about the stimulus wavelength; and the number of subsystems it recruits can be specified in terms of the amplitude of distribution or as a function of the luminosity. Thus we get the curve L which recruits red, yellow, and blue information in varying proportions.

Specifically, the recruitment curve L falls totally within the range of recruitment possiblities of both the blue and yellow systems since it is a complete subset of each. It is only a partial subset of red, with perhaps 20% overlap occurring.

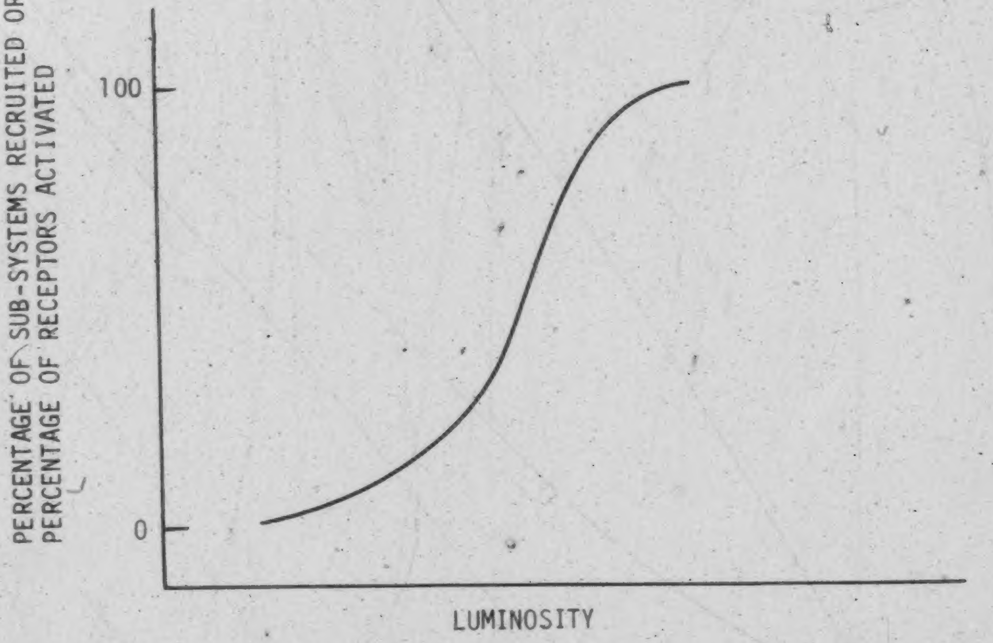

Figure 36. Percentage of neural sub-systems recruited in any primary color system as a function of luminosity.

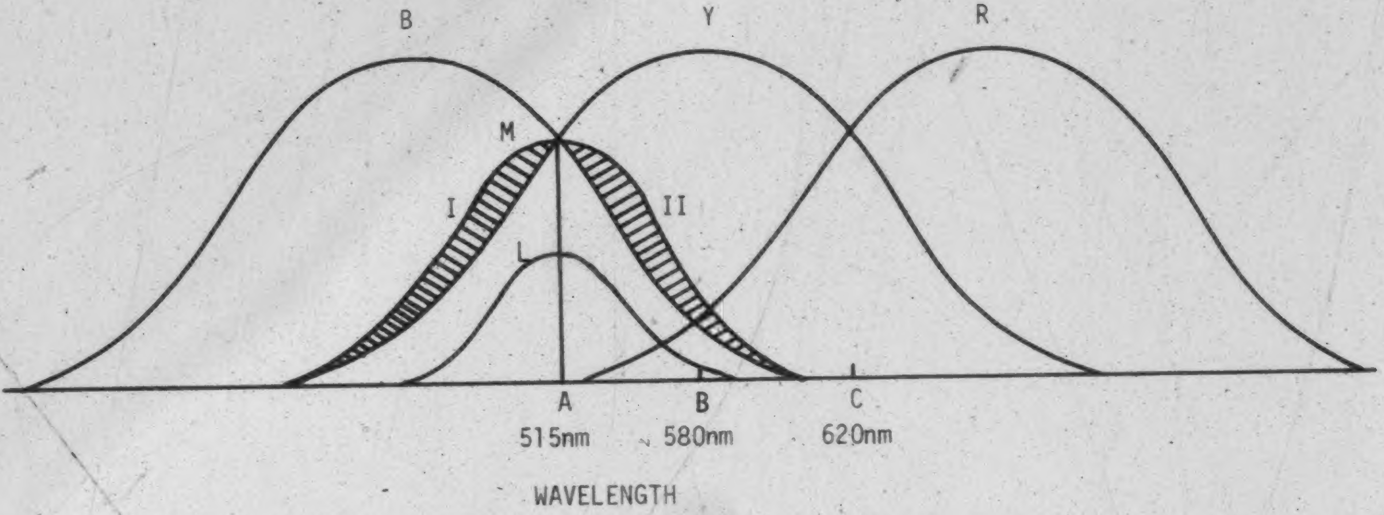

Figure 37. Neural recruitment model for desaturation. For L and M, the ordinate is the TT range. For B, Y, and R, the area under the curve represents the proportion of channels within each system which can be driven under the specific conditions of intermittency and wavelength defined by L and M.

The resulting mixture is a green of a high saturation. The saturation is determined by the color-whiteness ratio. The proportion of neural energy available to produce white information is limited by the smallest contribution of the three participating systems. The amount of saturation then, can be specified in terms of the ratios of red, yellow, and blue information. In this case recruitment involves 100% of the possible blue and yellow information and 20% of the possible red information. From these data, it is possible to derive a whiteness or non-purity exponent of 20/220 and a color purity exponent of 20/220.[9] The ratio of these exponents (0.100) represents a certain level of saturation.

If the possibility for neural production is increased at the same wavelength, either by increasing luminosity or by synchronizing channels through intermittency, much more neural potential is recruited from each system but the proportions change.

If the amplitude of the recruitment curve in fig. 37 is raised to DES threshold for example, curve M results where the total possible neural production is not a complete subset of any of the three color systems. Only about 80% of the possible blue and yellow information is recruited. The shaded areas, I and II, represent the other possible 20%. Note that the areas of I and II are equal indicating that the proportions of blue and yellow remain equal, even though they are reduced in relation to the proportion of red. As well, the proportion of red is increased slightly, to perhaps 30% since M intersects R at a steeper part of the R curve than did L.

Recruitment in this case involves 80% blue, 80% yellow and 30% red information. The whiteness exponent is 30/190 and the purity exponent is 160/190. The saturation ratio is 0.188 which represents a higher level of desaturation than 0.100.

Under M, a greater proportion of the neural energy is available to produce white information than under L.

SPECULATIVE EXPLANATION FOR HUE SHIFT

HS operates much the same as DES. The basic difference is, that when the neural potential for whiteness is extracted from the total, the remaining neural potential is not symmetrically distributed about the stimulus wavelength.

An example of HS is demonstrated in figure 38. If a stimulus is presented in a spectral area where negative hue shift occurs, for example at 600nm, neural potential is recruited in the same manner as it was for 515nm. The recruitment curve N is a total subset of R and Y and is a partial (=30%) subset of B. The resulting purity and

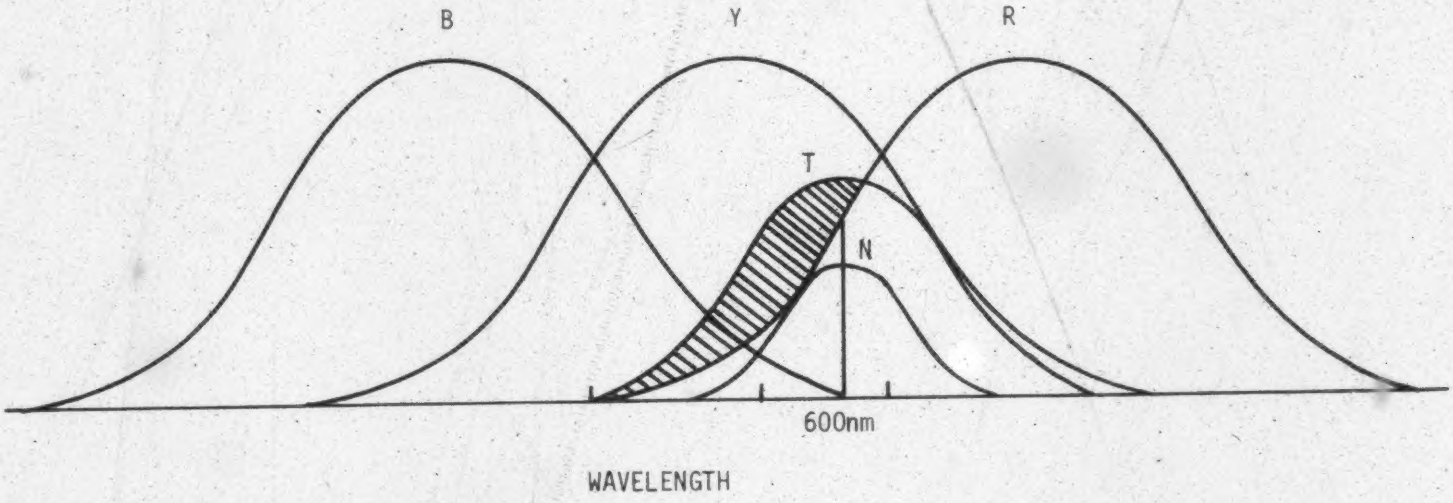

Figure 38. Neural recruitment model for hue shift.

non-purity exponents are 200/230 and 30/230 which yields a saturated orange.

When neural production is increased to T, all proportions change, including the relative proportions of Y and R. Y remains at 100% but R reduces to about 80% and B increases slightly to 40%. The new exponents show a higher ratio of non-purity to purity, only part of which, in this case, is interpreted by the system as DES. There is an overbalance of yellow neural information, and part of the purity-non-purity ratio is interpreted as a hue shift towards the yellow.

SCOPE OF THE GENERAL MODEL

This model accounts for much of the HS and DES data collected both by the author, and by the other investigators. A brief summary of its explanatory scope is presented here:

(1) It explains direction and magnitude of HS and DES in all parts of the spectrum.

(2) The neural recruitment model is in general accord with both the Bezold-Brücke shifts and the temporally-induced color shifts (HS and DES) since the directions and magnitudes of these shifts about the spectral anchor points are the same for both sets

of phenomena. The spectral loci of these points of no hue shift are different for HS and the Bezold-Brücke shifts, but this can be interpreted in terms of a transformation of wavelength scale, or through a spectral translocation of the neural recruitment curves (a type of TT locus shift) which arises as a function of photic intermittency.

(3) The TT model predicts that the luminosity threshold for Bezold-Brücke shifts will be higher than that for HS and DES; and that HS threshold will vary somewhat with the conditions of photic intermittency (fig. 29).

(4) It also explains the fact that the threshold for DES is higher than that for SS (fig. 5) since more subsystems from varying color systems are recruited in the production of DES.

(5) It predicts that BE will occur in the chromaticity system, along with either DES or HS, again through the recruitment of more sub-systems.

(6) It supports the notion that the yellow temporal range is shorter than the others; and that yellow in steady state is already more desaturated than the other colors. This is explained by a higher base level purity-non-purity exponent ratio for yellow

than for other systems through the recuitment of high proportions of red and blue information in the production of steady state yellow (consider exponent ratios for a recruitment curve L at 575nm, in figure 37A, spectral locus B).

(7) It can explain SS by a dimensional transformation of the integrative processes of neural recruitment from the three color systems. When considered in a non-temporal context, DES is produced through an increase in neural recruitment represented, by changes in the ordinate where increase in neural recruitment represented by changes in the ordinate where the abscissa (wavelength) remains fixed, as in figure 37. This representation however, is somewhat artificial as the real process, when considered in a temporal context, involves a collapse system in which the degree of overlap between the three color systems varies (fig. 39). The ordinate remains fixed and the abscissa contracts as a function of intermittency. SS can easily be incorporated in to this schema through an expansion of the abscissa as a function of SS intermittency conditions, to the point where the three color systems do not overlap for the particular luminosity level in question. It is convenient to outline the model the other way however, because it is conceptually difficult to isolate spectral

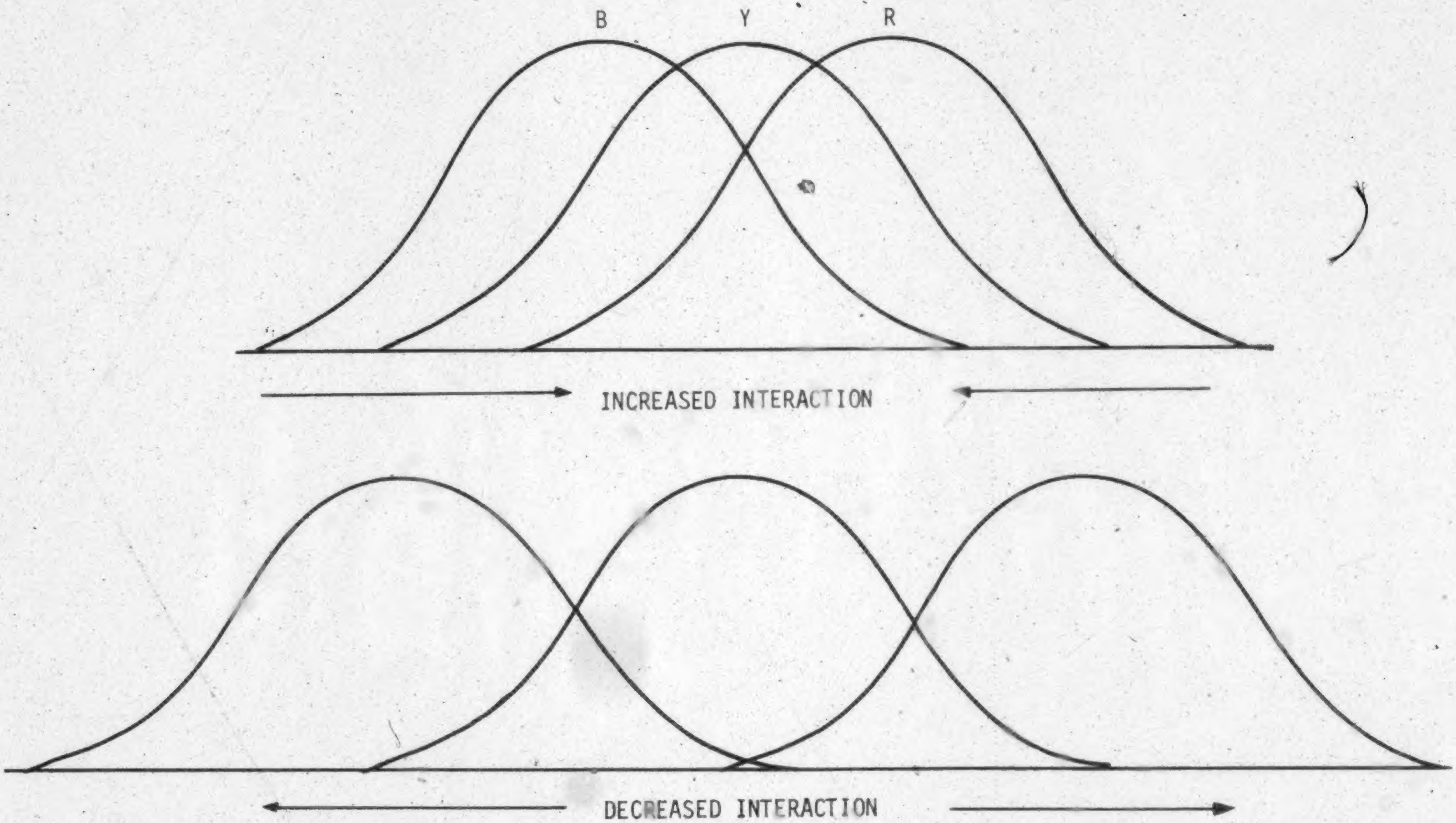

Figure 39. Dimensional transformation of the neural recruitment model.

dispersions from temporal dispersions on the abscissa.

OTHER POINTS OF DISCUSSION

1 Supersaturation decay rates for red, yellow, and green (fig. 16) are related to the VEP implicit times for these colors (Shipley, Jones, and Fry, 1966). They are also ordinally consistent with other data on neural processing times for various colors (Chang, 1950; Madsen and Lennox, 1955; etc.).

2 There is a certain body of evidence to suggest that above 620nm, and below 510nm, color changes may involve SS as well as HS towards the extreme ends of the spectrum. One such piece of evidence is found in the disagreement in direction of HS above 620nm by various investigators (Ball and Bartley, 1965; Nilsson and Nelson, 1971). Another is found within the present study, in smaller magnitudes of hue matches at these extreme wavelengths (fig. 9). Observers may have been confusing HS with SS here for both red and violet. In the collapse-recruitment model, these changes can be interpreted either way.

3 The data for magnitude of BE over wavelength (fig. 12) do not agree with those of Bartley (1965). This difference may have arisen from a higher luminosity

level, or from the use of double grating monochrometers in the present study which yield a more narrow waveband.

4 The magnitude of DES for each of the three primary colors (fig. 15) reflects the width of the TT range for these colors.

5 For Deutan, 425nm and 550nm (violet and green) seem to operate in similar fashion for hue matching (figs. 17, 18, 19A, 19C, and 20), and for desaturation (figs. 23 and 24); but not for brightness (fig. 22). These comparisons indicate that green and violet may be neurologically more closely related than red and green in dichromats.

6 Threshold curves for BE and the chromatic phenomena (fig. 5) further support the relative neural isolation of luminosity and chromaticity systems.

7 The shapes of the brightness curves for PCF in figure 10 suggest that in general, brightness is proportional to the luminous flux. At low rates of intermittency, where BE occurs, rate of intermittency and PCF interact to produce the BE effect. Since, for single pulses and rates above CFF, changes in PCF are equivalent to changes in luminosity, it is possible to conceive of a Bunsen-Roscoe, or Broca-Sulzer type of relationship between brightness, BE, and luminous flux as a function

of intermittency.

This completes the discussion of the results. Salient findings and interpretations are summarized in the following section.

SUMMARY AND CONCLUSIONS

Saturation is perhaps, a more important variable in color than people have suspected. Under steady illumination, it seems inextricably related to both hue and to whiteness. Under photic intermittency, however, changes in hue and saturation are related in an ordered, time-dependent way which reflects the operation of a single process for all color integration.

In this research, saturation has been considered in a temporal context. A temporal color space, based on color mixing processes, has been proposed as an alternative to existing Euclidean color spaces. The suggested temporal definition for saturation provides a framework for considering color mixing as a comparator mechanism which interprets information about the spatial organization of the environment. In the three dimensional world, edges, angles, shapes, and contours are perceptually defined to a great extent by abrupt changes in texture, brightness, and color gradients. Information from these changes is transduced into a system of neural processing latencies for the various types of input.

Under steady illumination, these latencies are optimally different for different colors. Under intermittency, information overload occurs, and more uniform latencies result. In short, the temporal comparator is not as efficient under intermittency. Desaturation and whiteness arise as elements of noise in the chromaticity system. Color deficiencies, such as deuteranopia may also be the result of harmonically induced noise in an imporperly tuned system.

FOOTNOTES

[0] The Bezold-Brücke effect involves hue shifts which occur in some spectral areas as a function of increased luminosity.

[1] These more recent sensory aids are abstractive to an extent since they transduce sensory information in different modes.

[2] The Ladd-Franklin (1929) color theory provides an evolutionary analogy to this development in color naming systems.

[3] The cycle duration is similar to that of the alpha-rhythm. Various theoretical connections between alpha and this periodicity have been developed since 1933, however, recent work by Andersson and Andersen (1969) suggests that they are not related.

[4] The variacs were set at line voltage and used only for pilot work, and in some tests for fine tuning and equalization of the target luminosities. The necessity for gross changes in luminosity precluded the general use of variacs since resulting color temperature changes affected corresponding hues.

[5] Thresholds for HS, DES, and BE were taken first. The SS threshold was taken later.

[6] Resulting color temperature changes were small and did not affect hue since (A) voltage changes were small and (B) monochrometers were situated downstream from the lamps. This was tested by comparing these reductions with equivalent ND reductions.

[7] This involved simultaneously varying wavelength and compensating for luminosity by changing ND filters. The procedure was somewhat awkward.

[8] The distribution is assumed to be symmetrical here for the purposes of demonstration.

[9] This is a simplified version as one is not strictly a purity exponent and the other is not strictly a whiteness exponent.

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APPENDIX I

DATA TABLES

A. Trichromat Data, Tables 1-14

B. Deutan Data, Tables 15-21

TABLE 1

LUMINOSITY AS A FUNCTION OF WAVELENGTH (see fig. 4)

WAVELENGTH	$\overline{X}$ LOG LUMINOSITY ABOVE THRESHOLD					
in nm	MG	BJ	DN	SM	GT	AJ
650	3.9	3.9	4.0	3.6	3.5	
625	4.4	4.3	4.3	4.3	4.0	2.7
600	4.6	4.7	4.6	4.8	4.4	
575	4.6	4.8	5.1	4.9	5.0	3.5
550	4.7	5.0	5.2	4.9	5.4	
525	4.8	5.2	5.3	5.0	4.8	2.8
500	4.7	5.0	5.1	4.9	5.1	
475	4.5	4.3	4.5	4.6	4.8	
450	4.2	3.6	4.3	4.4	3.6	
425	3.4	3.2	3.6	3.4	3.8	
400	1.9	1.9	2.5	2.1	2.2	

TABLE 2

LUMINOSITY THRESHOLDS FOR BE, DES, SS, AND HS AS A FUNCTION OF WAVELENGTH (see fig. 5)

PHENOMENON		WAVELENGTH IN nm							
	S	475	500	525	550	575	600	625	650
	BJ	2.9	3.4	3.6	3.7	3.9	3.5	3.3	2.9
BE	MG	3.2	3.5	3.7	4.0	3.8	3.6	3.2	2.9
	DN	3.1	3.3	3.6	3.8	3.8	3.7	3.3	2.8
	SM	3.1	3.2	3.5	3.9	3.9	3.7	3.1	2.7
	BJ	2.5	3.0		2.9		2.9		2.6
HS	MG	2.4	2.9		3.2		3.1		2.6
	DN	2.6	2.9		3.0		3.1		2.4
	SM	2.4	2.8		2.8		3.0		2.5
	BJ	2.2	2.7	2.8	2.5	2.3	2.7	2.6	2.4
DES	MG	2.1	2.6	2.7	2.6	2.2	2.6	2.7	2.5
	DN	2.1	2.8	2.9	2.5	2.3	2.8	2.7	2.3
	SM	2.2	2.7	2.6	2.4	2.3	2.4	2.5	2.3
	BJ	1.9	2.1	2.3	2.2	1.8	2.1	2.2	2.0
SS	MG	1.8	2.2	2.2	2.1	1.7	2.2	2.1	1.9
	DN	1.7	2.0	2.4	2.2	1.6	2.2	2.3	2.1
	SM	1.8	2.1	2.1	2.2	1.9	2.1	2.0	1.8

TABLE 3

REPORTED DIRECTION OF HUE SHIFT AS A FUNCTION OF WAVELENGTH (see fig. 6)

WAVELENGTH in nm	DIRECTION ($\overline{X}$ over repeated measures and Ss) 3 Hz	10 Hz
640	+	-
630	+	-
620	=	=
610	-	-
600	-	-
590	-	-
580	=	=
570	+	+
560	+	+
550	+	+
540	+	+
530	+	+
520	=	=
510	=	=
500	-	-
490	-	-
480	-	-
470	-	-

TABLE 4

HUE MATCHES AS A FUNCTION OF WAVELENGTH FOR STEADY ILLUMINATION AND 10 Hz, 0.25 PCF (see fig. 7)

WAVELENGTH	HUE MATCH ($\bar{X}$ error in nm)							
in nm	MG		BJ		DN		SM	
Rate	s	10	s	10	s	10	s	10
650	0.2	-8.0	0.7	-3.8	0.7	-5.0	1.0	-4.0
620	1.0	-0.7	0.4	-2.0	-0.7	-1.0	-0.2	-1.5
600	1.1	-6.0	-0.4	-5.0	-0.7	-7.0	1.0	-7.0
575	0.5	-0.3	0.0	-1.4	-0.7	-1.0	-0.8	-0.7
545	-0.7	4.0	-0.2	4.0	0.5	6.0	0.4	7.0
520	0.0	1.8	-0.5	1.0	0.2	0.2	0.7	1.0
475	-0.3	-3.0	-0.7	-1.8	0.7	-3.5	0.0	-3.8

TABLE 5

COMPARED MAGNITUDE OF HS AS A FUNCTION OF WAVELENGTH (see fig. 8)

TEST	WAVELENGTH WITH LARGER HS			
WAVELENGTHS (nm)	MG	BJ	DN	SM
475 x 495	475	475	475	475
530 x 545	545	545	=	545
545 x 563	545	=	563	545
587 x 600	600	600	600	587
600 x 610	600	600	600	=
635 x 650	650	=	650	650

Data for 510, 520, 575, and 620nm from Table 3.

TABLE 6

MAGNITUDE OF HS AS A FUNCTION OF WAVELENGTH
(see fig. 9)

WAVELENGTH	HS $\overline{X}$ error over 10 rep. Measures			
in nm	MG	BJ	DN	SM
475	6.1	4.2	3.3	3.6
495	4.1	4.3	2.9	3.1
510	0.7	1.2	0.4	0.5
530	2.3	2.5	2.8	3.4
545	4.3	3.8	5.3	6.1
560	4.0	2.8	4.2	4.1
580	1.3	0.8	0.7	1.1
587	6.8	4.4	6.5	6.0
600	6.3	4.8	7.2	6.5
610	3.2	2.7	4.1	3.4
620	0.6	0.9	0.2	1.1
635	3.5	3.8	4.4	4.2
650	4.0	4.5	4.6	4.8

TABLE 7

BRIGHTNESS AS A FUNCTION OF RATE AND PCF (see fig. 10, ordinal data $\overline{X}$ over $\underline{S}$s)

COMPARISON	BRIGHTNESS OF HIGHER RATE (compared with lower)			
RATES in Hz	PCF 0.75	0.50	0.25	0.125
1 x 0	+	+	+	-
2 x 0	+	+	+	-
3 x 0	+	+	+	-
4 x 0	+	+	+	-
5 x 0	=	+	=	-
6 x 0	-	=	-	-
7 x 0	-	-	-	-
8 x 0	-	-	-	-
9 x 0	-	-	-	-
10 x 0	-	-	-	-
15 x 0	-	-	-	-
20 x 0	-	-	-	-
CFF(30) x 0	-	-	-	-
1 x 2	+	+	+	+
2 x 3	+	+	+	+
3 x 4	+	+	+	+
4 x 5	+	+	+	+
5 x 6	+	+	+	+
6 x 7	+	+	+	+
7 x 8	+	+	+	-
8 x 9	+	=	-	-
9 x 10	+	=	-	-
10 x 15	+	+	+	+
15 x 20	+	+	+	+
20 x CFF	=	=	=	=

TABLE 8

BRIGHTNESS X RATE AS A FUNCTION OF TALBOT LEVEL BRIGHTNESS (see fig. 10)

(A) TALBOT LEVEL PCF	(B) TEST PCF	RATE AT WHICH BRIGHTNESS OF B = THAT OF A (in Hz)
0.75	0.50	10
	0.25	7
	0.125	3
0.50	0.25	15
	0.125	10,5
0.25	0.125	15

TABLE 9

BRIGHTNESS AS A FUNCTION OF PCF

(see figs. 10, 11, $\overline{X}$ over Ss)

PCF COMPARISONS	BRIGHTNESS OF THE LARGER PCF 3 HZ	10 HZ	CFF
0.75 X 0	+	-	-
0.50 X 0	+	-	-
0.25 X 0	+	-	-
0.125X 0	-	-	-
0.75 X 0.50	-	+	+
0.50 X 0.25	+	+	+
0.25 X 0.125	+	+	+
0.75 X 0.25	-	+	+

TABLE 10

BRIGHTNESS ENHANCEMENT AS A FUNCTION OF WAVELENGTH
(T+4 log)
(ordinal nm comparisons $\overline{x}$ over Ss, see fig. 12)

WAVELENGTH COMPARISON in nm	BRIGHTNESS OF LONGER nm IN COMPARISON 10Hz, 0.50 PCF	10 Hz, 0.25 PCF
450 x 475	+	+
475 x 500	+	+
500 x 525	+	+
525 x 550	+	+
550 x 575	-	-
575 x 600	-	-
600 x 625	-	-
625 x 650	-	-
a* 525 x 575	=	=
b* 500 x 600	=	=
c* 650 x 450	=	=

*auxiliary comparisons set after main data was collected.

TABLE 11

SATURATION AS A FUNCTION OF RATE AND PCF

(see fig. 13)
(ordinal comparisons, $\bar{X}$ over $\underline{S}$s and wavelengths)

COMPARISON RATE IN HZ	SATURATION OF GREATER RATE (COMPARISON) PCF 0.75	0.50	0.25	0.125
1 X 0	+	+	+	+
2 X 0	+	+	+	+
3 X 0	+	+	=+	-
4 X 0	+	=	=	-
5 X 0	-	-	-	-
6 X 0	-	-	-	-
7 X 0	-	-	-	-
8 X 0	-	-	-	-
9 X 0	-	-	-	-
10 X 0	-	-	-	-
12 X 0	-	-	-	-
15 X 0	-	-	-	-
20 X 0	-	-	-	-
CFF X 0	=	=	=	=
	saturation of lower rate			
1 X 2	=	-	=	=
2 X 3	-	+	+	+
3 X 4	=	+	+	+
4 X 5	+	+	+	+
5 X 6	+	+	+	+
6 X 7	+	+	+	+
7 X 8	=	=	=	-
8 X 9	=	-	-	-
9 X 10	=	-	-	-
10 X 12	-	-	-	-
12 X 15	-	-	-	-
15 X 20	=	-	-	-
CFF X 20	-	-	-	-
A* 6 X 10	=	=	=	-
B* 5 X 12	+	=	+	=
C* 4 X 15	+	+	+	=

*AUXILIARY TESTS A, B, C DETERMINED AFTER THE ORIGINAL DATA WERE ANALYZED.

TABLE 12

SATURATION AS A FUNCTION OF PCF

(see figs. 13, 14)
(ordinal comparison data, $\overline{X}$ over Ss and wavelength)

PCF	SATURATION OF LARGER PCF (comparison)				
Comparison	3 Hz	5 Hz	10Hz	20Hz	CFF
0.125 x 0	+	−	−	−	=
0.25 x 0	+	−	−	−	=
0.50 x 0	+	−	−	−	=
0.75 x 0	+	−	−	−	=
0.125 x 0.25	−	=	+	+	=
0.25 x 0.50	−	=	+	+	=
0.50 x 0.75	+	−	−	−	=
0.75 x 0.25	−	+	+	+	=

TABLE 13

ORDINAL MAGNITUDE OF DES AND SS** AS A FUNCTION OF WAVELENGTH (see fig. 15)

COMPARISON WAVELENGTH (nm)	SATURATION (magnitude comparison of larger nm)							
	MG		BJ		DN		SM	
	DES	SS	DES	SS	DES	SS	DES	SS
475 x 500	+	-	+		+		+	-
500 x 515	+		=		+		=	
515 x 525	-		=		-		-	
500 x 525	=	+	=		=		=	+
525 x 550	-	+	-		-		-	+
550 x 575	-	+	-		-		-	=
575 x 600	+	+	+		+		+	+
600 x 610	+		+		+		=	
610 x 625	+		+		+		+	
625 x 637	-		=		-		-	
600 x 625	+	+	+		+		+	+
625 x 650	-	+	-		-		-	=
637 x 650	-		-		-		-	
a* 475 x 575	+		=		-		-	
b* 575 x 650	=		=		=		-	
c* 515 x 625	+		+		+		+	

*auxilliary comparisons for DES
**SS data incomplete

TABLE 14

SUPERSATURATION DECAY TIMES FOR
515nm, 580nm, and 620nm (see fig. 16)

Pulse length in ms*	SATURATION AT END OF STIMULUS INTERVAL (compared with steady) 620nm	580nm	515nm
5400	=	=	=
4500	=	=	=
3000	=	=	=
2250	=	=	=
1500	=	=	=
1400	=	=	=
1350	=	=	=
1300	=	=	=
1250	=	=	+=
1200	=	+=	+=
1175	+=	+=	+=
1150	+=	+=	+=
1100	+=	+=	+=
1050	+=	+=	+=
1000	+	+	+
950	+	+	+
850	+	+	+
750	+	+	+
500	+	+	+
375	+	+	+
250	+	+	+
125	+	+	+

*Rates and PCF's transformed into pulse and interstimulus interval times. SS did not occur when the null interval was less than 125ms.

TABLE 15

DEUTAN HUE MATCHES AS A FUNCTION OF WAVELENGTH FOR STEADY ILLUMINATION AND 10 Hz, 0.25 PCF

(see figs. 17, 18)

WAVELENGTH in nm	HUE MATCH RANGE ($\bar{X}$ error in nm) STEADY	10 Hz
650	-5, 5	-18,12
625	-3, 4	-34,-12
600	-6,11	-22,-12
575	-4, 9	-25,26
550	-28,42	-21,22
525	-4, 5	-6,10
500	-2, 3	0, 4
475	-2, 5	-8,10
450	-6, 5	-1, 5
425	-12,28	-8,18

TABLE 16

DEUTAN HUE SHIFT AS A FUNCTION OF RATE IN FOUR SPECTRAL AREAS (see fig. 19)

Hue Match Range ($\overline{X}$ error in nm)

RATE	425 nm		500 nm		550 nm		625 nm	
in Hz	Loci	range	Loci	range	Loci	range	Loci	range
2.4	2,48	46	-12,11	23	-23,18	41	-8, 24	32
3.5	-13,43	56	-2,12	14	-18,18	36	-18, 7	25
4.5	-2,35	37	0,21	21	-14,29	43	-29, -4	25
5.8	11,40	29	3,18	15	-2,24	26	-40,-21	19
7.0	8,36	28	-3,14	17	2,16	14	-64,-25	39
8.0	2,24	22	5,12	7	-2,17	19	-73,-28	45
8.8	1,30	29	-1,10	9	-8,15	23	-69,-21	48
10.0	9,42	31	-1,12	13	-14,17	31	-56,-16	40
15.0	1,39	38	-3,14	17	-34,22	56	-19, 6	25

TABLE 17

DEUTAN HUE MATCH ERRORS AS A FUNCTION OF PCF

(550nm, 5.8 Hz, see fig. 21)

PCF	HUE MATCH RANGE ($\overline{X}$ error in nm)	
	LOCI	RANGE
0.125	5,35	30
0.25	1,36	35
0.50	-2,24	26
0.75	-13,27	40

TABLE 18

DEUTAN BRIGHTNESS AS A FUNCTION OF RATE IN FOUR SPECTRAL AREAS (see fig. 22)

RATE	BRIGHTNESS OF HIGHER RATE			
COMPARISONS	425nm	500nm	550nm	625nm
1 x 0	=	-	=	+
3 x 0	=	+	=	+
5 x 0	-	-	-	-
7 x 0	-	-	-	-
10 x 0	-	-	-	-
12 x 0	-	=	-	-
15 x 0	-	=	=	=
18 x 0	-	-	-	-
20 x 0	-	-	-	-
CFF x 0	-	-	-	-
1 x 3	=	+	=	-
3 x 5	-	-	-	-
5 x 7	-	-	-	-
7 x 10	+	+	=	+
10 x 12	+	+	-	+
12 x 15	+	=	-	+
15 x 18	-	-	-	-
18 x 20	-	-	-	-
20 x CFF	=	=	=	=

TABLE 19

SATURATION AS A FUNCTION OF RATE FOR DEUTAN (see fig. 23)

RATE IN HZ	SATURATION (comparison of higher rate)			
	425nm	500nm	550nm	625nm
1 x 0	+	=	+	+
3 x 0	+	+	+	+
5 x 0	-	=	-	-
7 x 0	-	=	-	-
10 x 0	+	-=	+	-
12 x 0	+	-	+	-
15 x 0	+	-	+	-
18 x 0	+	=	=	-
20 x 0	=	=	=	-
CFF x 0	=	=	=	=
1 x 3	=	+	-	=
3 x 5	-	-	-	-
5 x 7	+	=	+	+
7 x 10	+	=-	+	+
10 x 12	+	-	+	+
12 x 15	+	=	-	-
15 x 18	-	+	-	-
18 x 20	-	=	=	=
20 x CFF	=	=	=	+

TABLE 20

SATURATION AS A FUNCTION OF PCF FOR DEUTAN (see figs. 23,24)

PCF	SATURATION (comparison of larger PCF)											
Comparison	425nm			500nm			550nm			625nm		
	3	10	F	3	10	F	3	10	F	3	10	F
0.125 x 0	-	-	=	-	=	=	-	=	=	-	=	=
0.25 x 0	+	-	=	=	=	=	+	+	=	+	-	=
0.50 x 0	+	+	=	=	=	=	+	+	=	+	-	=
0.75 x 0	+	+	=	+	-	=	+	+	=	+	-	=
0.75 x 0.50	-	-	=	+	-	=	-	-	=	-	+	=
0.50 x 0.25	+	+	=	=	=	=	+	+	=	+	-	=
0.25 x 0.125	+	=	=	+	=	=	+	+	=	+	-	=
0.75 x 0.25	-	+	=	+	-	=	-	-	=	-	+	=

TABLE 21

DESATURATION AS A FUNCTION OF WAVELENGTH FOR DEUTAN (see fig. 25)*

COMPARISON WAVELENGTH (nm)	CHANGE IN SATURATION (comparison of larger nm)
650 x 625	-
625 x 600	+
600 x 575	+
575 x 550	-
550 x 525	-
525 x 500	+
500 x 475	=
475 x 450	-
450 x 425	-
425 x 400	+

*ordinal comparisons of magnitude for 625, 550, 500, and 425nm were taken from data in Table 19.

APPENDIX II

RETINITIS PIGMENTOSA STUDY

A sixth observer, AJ, was examined in an auxiliary study. He had Retinitis Pigmentosa, a rare genetically-based disease which degenerates receptor pigment progressively from the periphery of the retina to the fovea. At the time of the experiment, luminosity and perimetry tests showed this disease had completely deteriorated his scotopic vision, but left his photopic vision intact.

Studies of AJ's color experiences under intermittency were fragmentary. Luminosity ratings were taken for 3 wavelengths (620, 580, and 515nm) and responses were noted under conditions which optimally produced BE, DES, and SS in the trichromats.

FINDINGS

AJ had a reduced luminosity level due to the loss of scotopic pigment (see Table 1, Appendix I). Under 10 Hz, 0.50 PCF he detected both BE (at 575 and 625nm) and HS (at 560 and 600nm) in the same directions and approximate magnitudes as normal trichromats. He also detected SS at 3 Hz, 0.50 Hz (at 525, 575, and 625nm) but did not report

DES for any wavelength or for any conditions of intermittency from 1 Hz to CFF. This suggests that the luminosity system is involved in the production of DES under intermittency, but not necessarily in BE, which has important implications for experiential results of luminosity-chromaticity interactions.

APPENDIX III

GLOSSARY OF TERMS

Definitions from the Dictionary of Visual Science (Shapero, Cline, and Hofstetter, 1968) are given here for various technical terms used in this thesis.

Brightness. The subjective attribute of any light sensation giving rise to the percept of luminous intensity, including the whole scale of qualities of being bright, light, brilliant, dim, or dark.

Brightness enhancement (BE, the Brücke-Bartley effect). The increased brightness of intermittent stimulation (illumination) over continuous illumination of the same intensity.

Color. 1. A senory or perceptual component of visual experience, characterized by the attrubutes of hue, brightness, and saturation, and usually arising from, or in response to, stimulation of the retina by radiation of wavelengths between about 380 and 760 mμ. Sensory components, such as white, gray, and black, which have neither hue nor saturation, are sometimes included with colors. Variously synonymous with hue, tint, or shade. 2. A stimulus or a visual object which evokes a chromatic response.

Critical fusion frequency (CFF). The rate of presentation of intermittent, alternate or discontinuous photic stimuli that just gives rise to a fully uniform and continuous sensation obliterating the flicker.

Desaturation. The apparent bleaching of a hue under photic intermittency.

Deuteranomaly. A form of anomalous trichromatism in which an abnormally large proportion of green is required in a mixture of red and green light to match a given yellow. In the green to red region of the spectrum, hue discrimination is poor, and colors appear relatively more desaturated to the deuteranomal than they do to the normal trichromat, leading to confusion of light tints or of very dark shades of these color.

Episcotister. A sectored disk which may be rotated in front of a light source to produce flashes of light. It is used in the study of the critical flicker frequency.

Hue. The attribute of color sensation ordinarily correlated with wavelength or combinations of wavelengths of the visual stimulus and distinguished from the attributes brightness and saturation.

Hue shift. The apparent change in hue under photic intermittency.

Pulse-to-cycle fraction (PCF). The light-dark ratio, or the proportion of time within a photic cycle that the stimulus is present.

Retinitis Pigmentosa. A primary degeneration of the neuroepithelium of the retina with subsequent migration of the retinal pigment. The ophthalmoscopic appearance is of individual clumps of black pigment peripherally located and shaped like bone corpuscles, attenutated retinal vessels, and a pale waxy optic disk. The main symptoms are night blindness and progressive contraction of the visual field. It is familial, of unknown etiology, and usually bilateral.

Saturation. The quality of visual perception which permits a judgement of different purities of any one dominant wavelength; the degree to which a chromatic color differs from a gray of the same brightness.

Subjective color. The sensation of color derived from stimulation other than with chromatic stimuli, as may occur from intermittent exposure at low frequencies to achromatic stimuli or from exposure to dazzling lights.

Supersaturation. The apparent increase in purity of a hue under photic intermittency.

Talbot level brightness (Talbot effect). The experience of continuous light from a rapidly intermittent source, but of an intensity equivalent to that produced if the total amount of light were equally distributed in time; the phenomenon giving rise to Talbot's law.

Temporal tuning (in the visual system). The notion that some structures in the visual system are designed to process visual information better under certain time conditions than under others.